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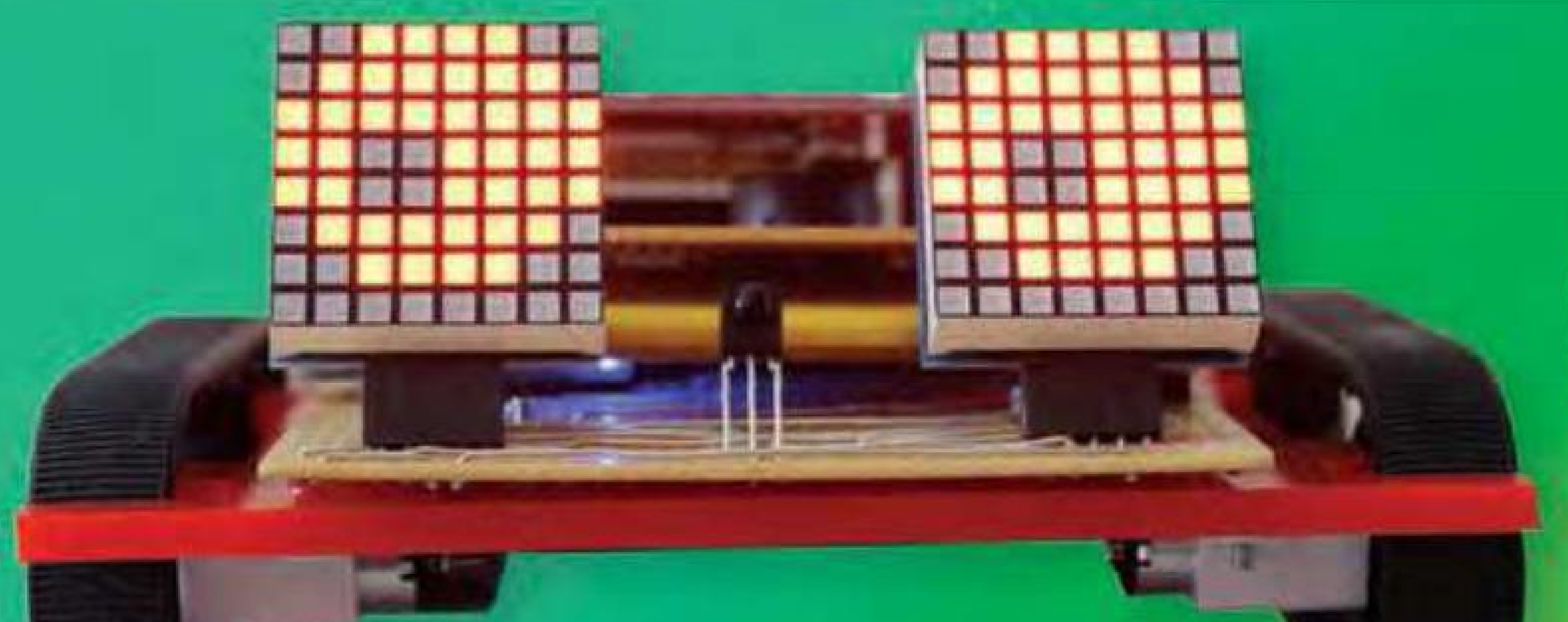

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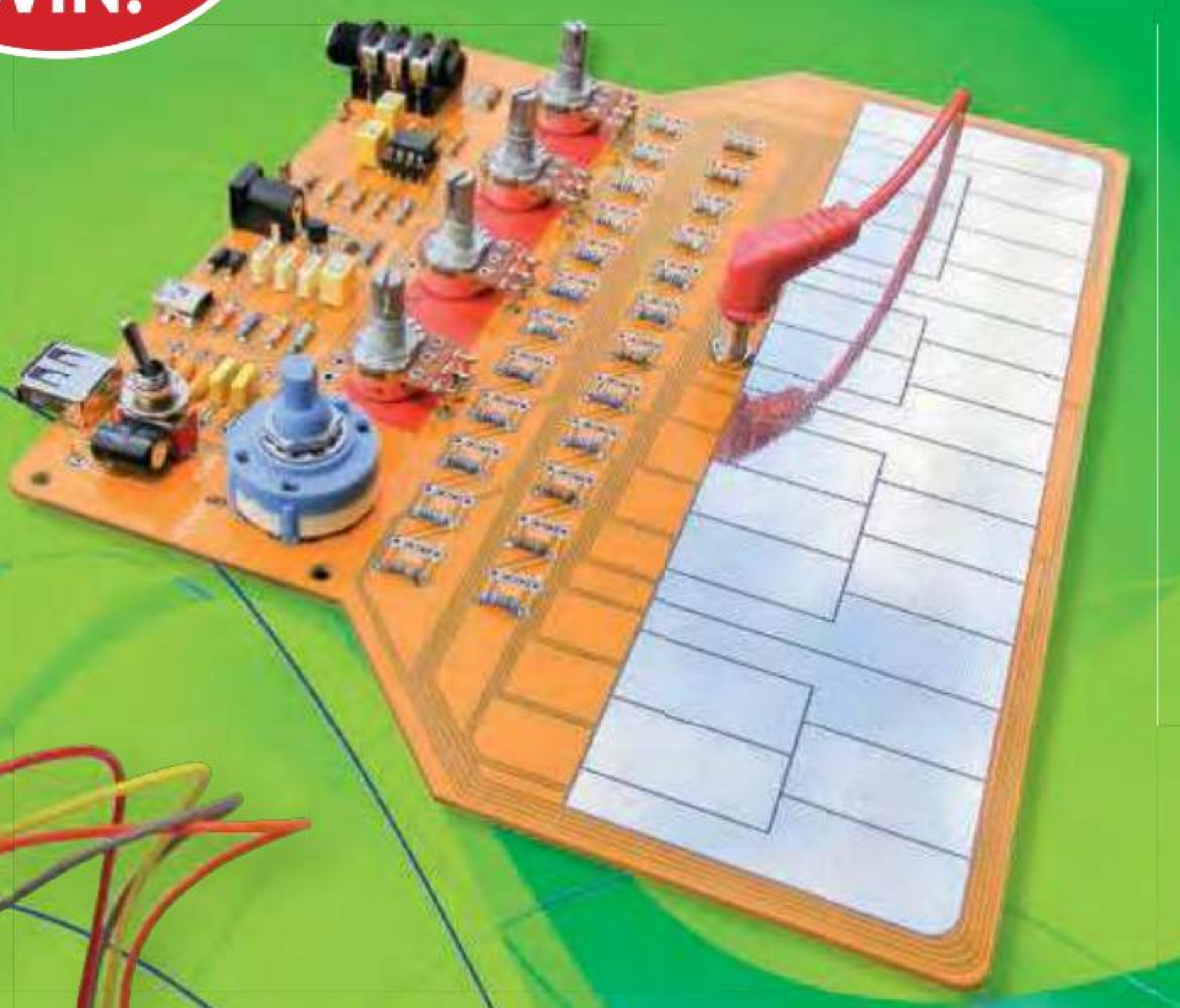

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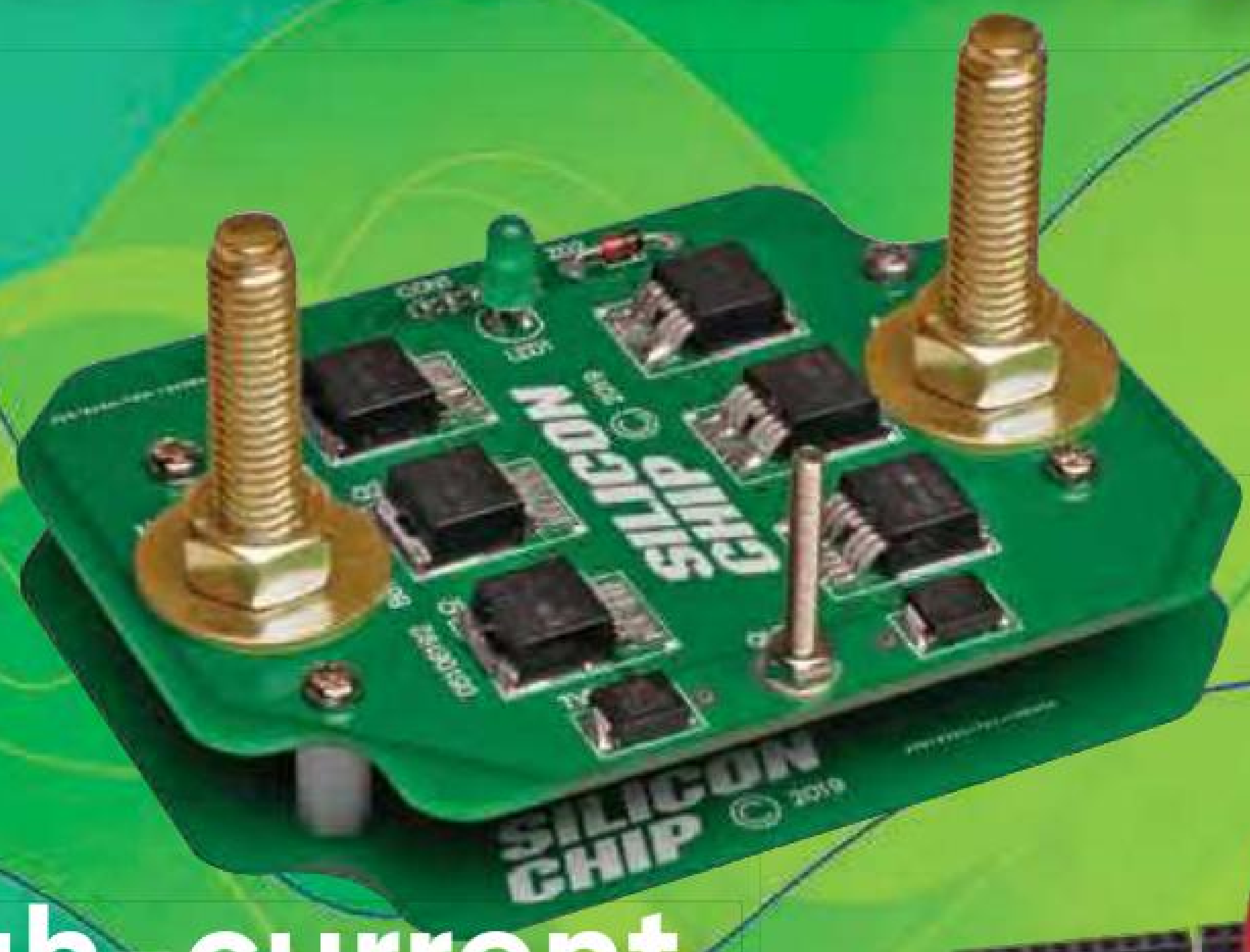

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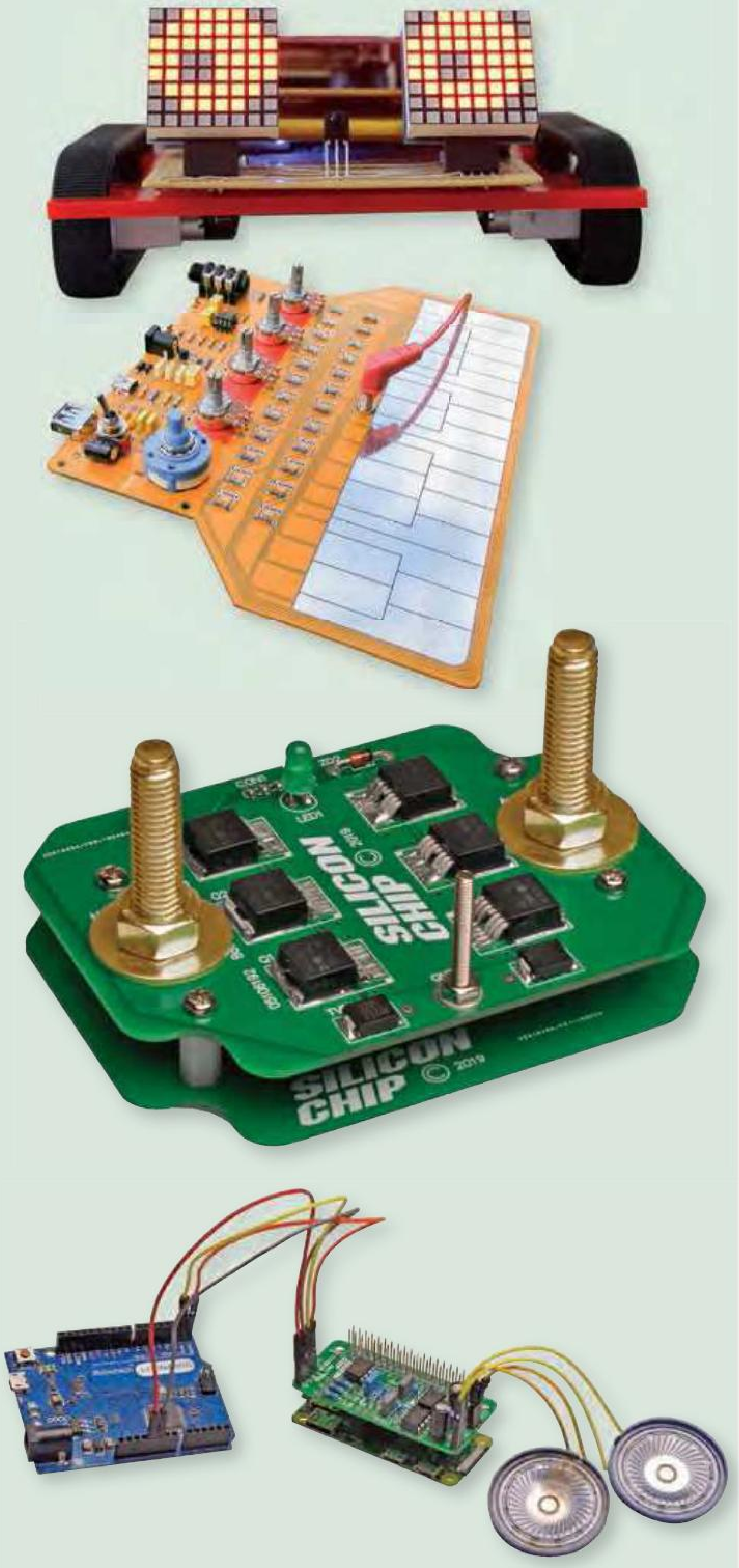

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WIRELESS FOR THE WARRIOR

by LOUIS MEULSTEE

THE DEFINITIVE TECHNICAL HISTORY OF RADIO COMMUNICATION EQUIPMENT IN THE BRITISH ARMY

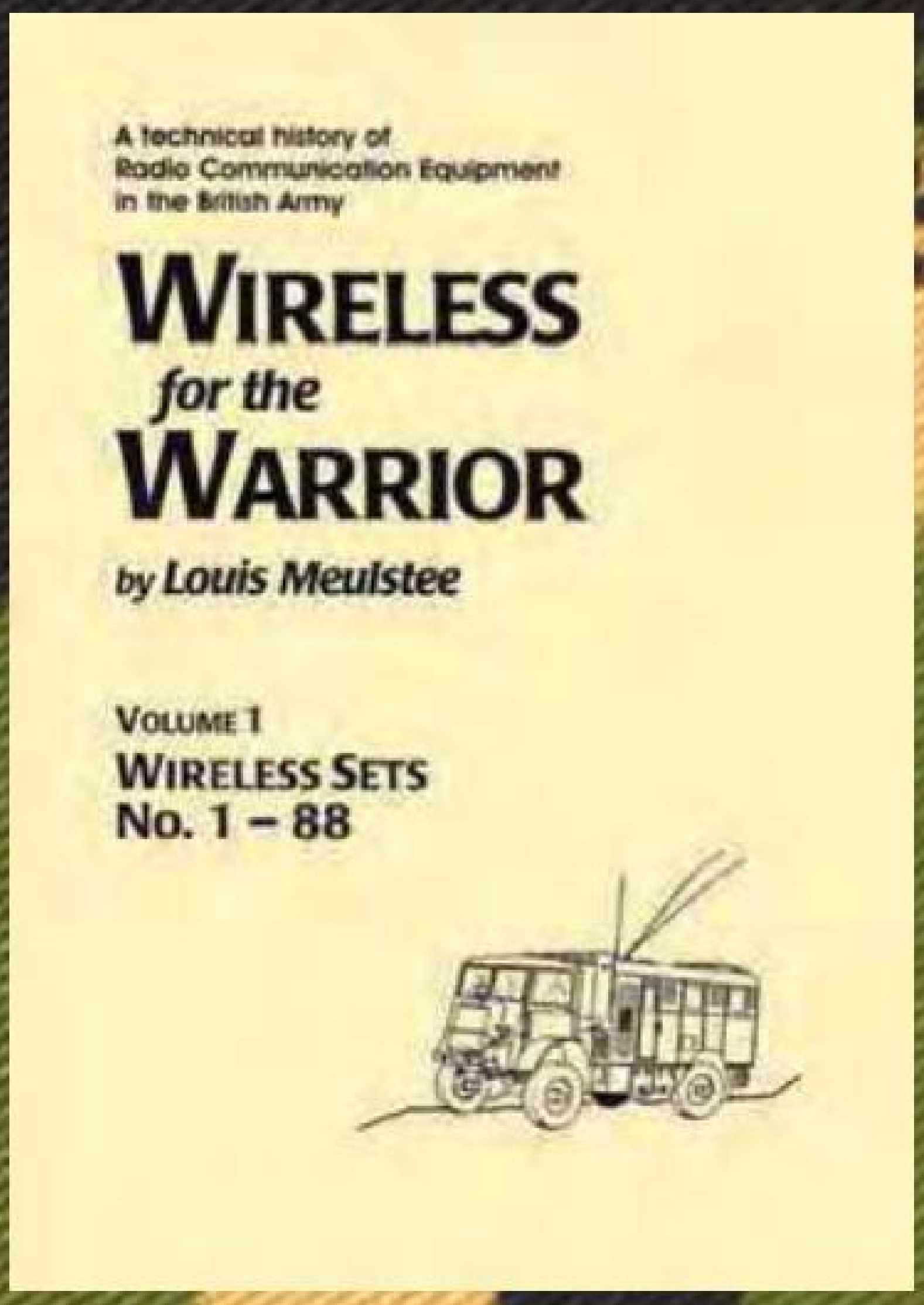
The *Wireless for the Warrior* books are a source of reference for the history and development of radio communication equipment used by the British Army from the very early days of wireless up to the 1960s.

The books are very detailed and include circuit diagrams, technical specifications and alignment data, technical development history, complete station lists and vehicle fitting instructions.

Volume 1 and *Volume 2* cover transmitters and transceivers used between 1932-1948. An era that starts with positive steps taken to formulate and develop a new series of wireless sets that offered great improvements over obsolete World War I pattern equipment. The other end of this timeframe saw the introduction of VHF FM and hermetically sealed equipment.

Volume 3 covers army receivers from 1932 to the late 1960s. The book not only describes receivers specifically designed for the British Army, but also the Royal Navy and RAF. Also covered: special receivers, direction finding receivers, Canadian and Australian Army receivers, commercial receivers adopted by the Army, and Army Welfare broadcast receivers.

Volume 4 covers clandestine, agent or 'spy' radio equipment, sets which were used by special forces, partisans, resistance, 'stay behind' organisations, Australian Coast Watchers and the diplomatic service. Plus, selected associated power sources, RDF and intercept receivers, bugs and radar beacons.



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in the British Army

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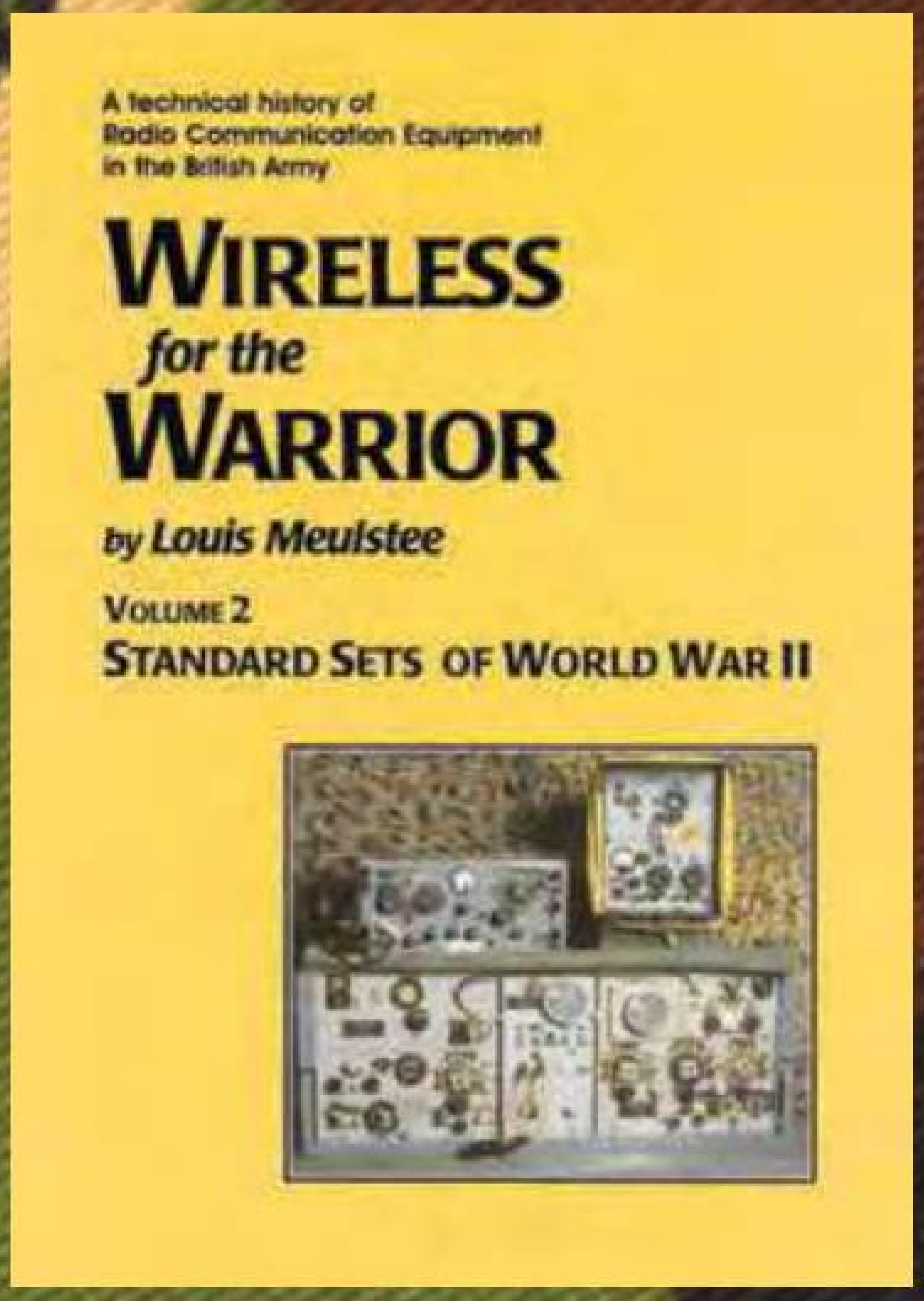

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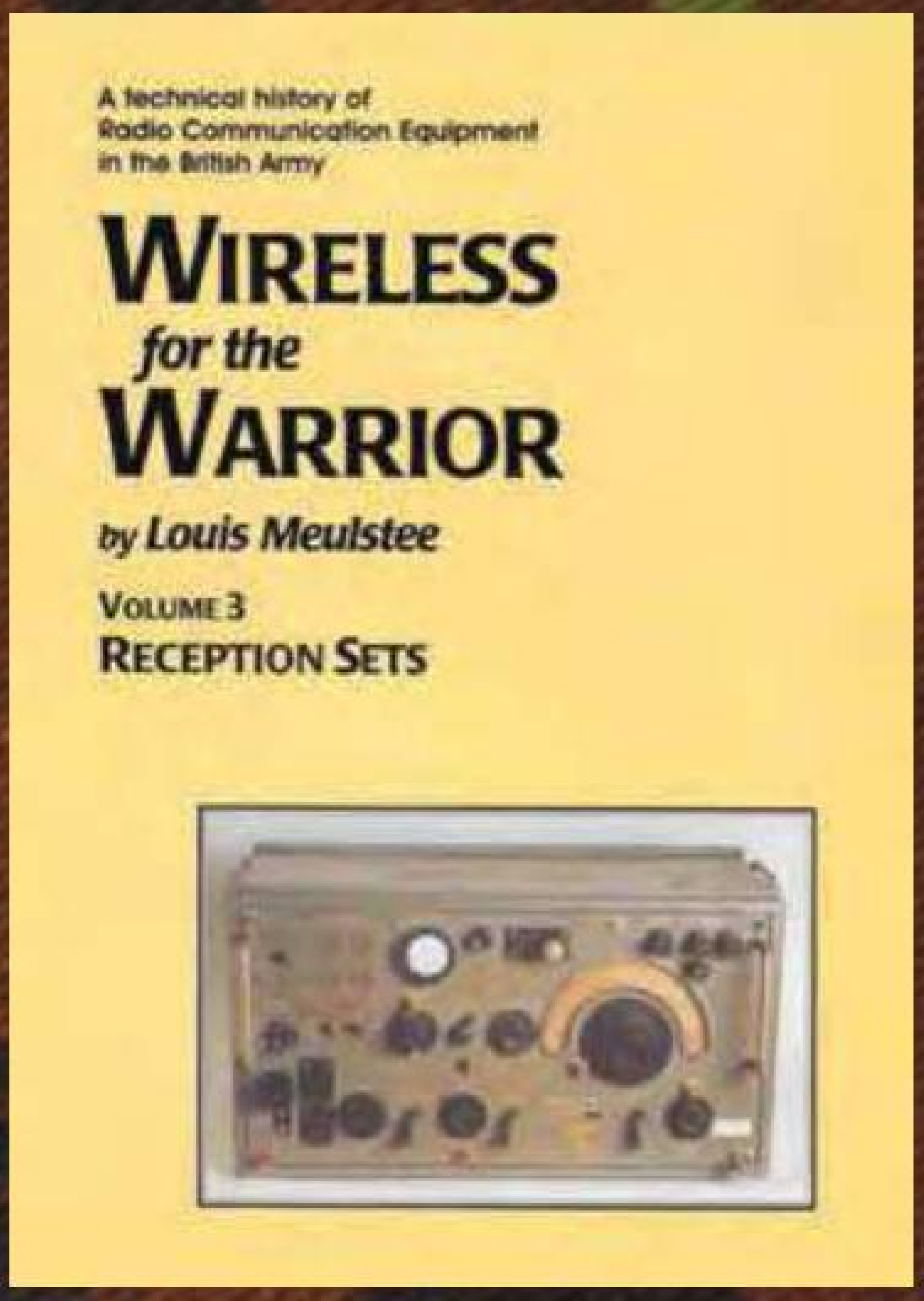

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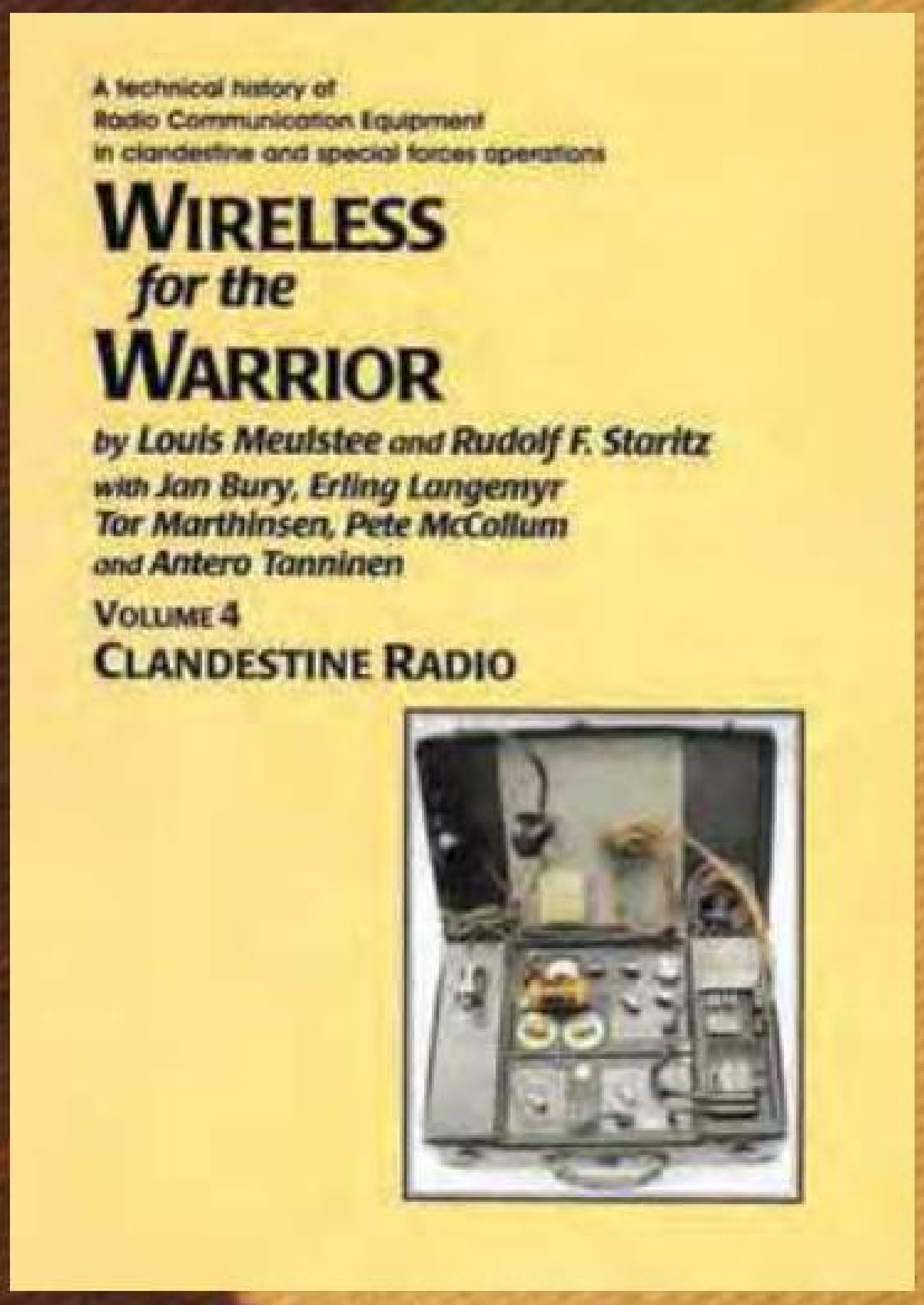

A technical history of
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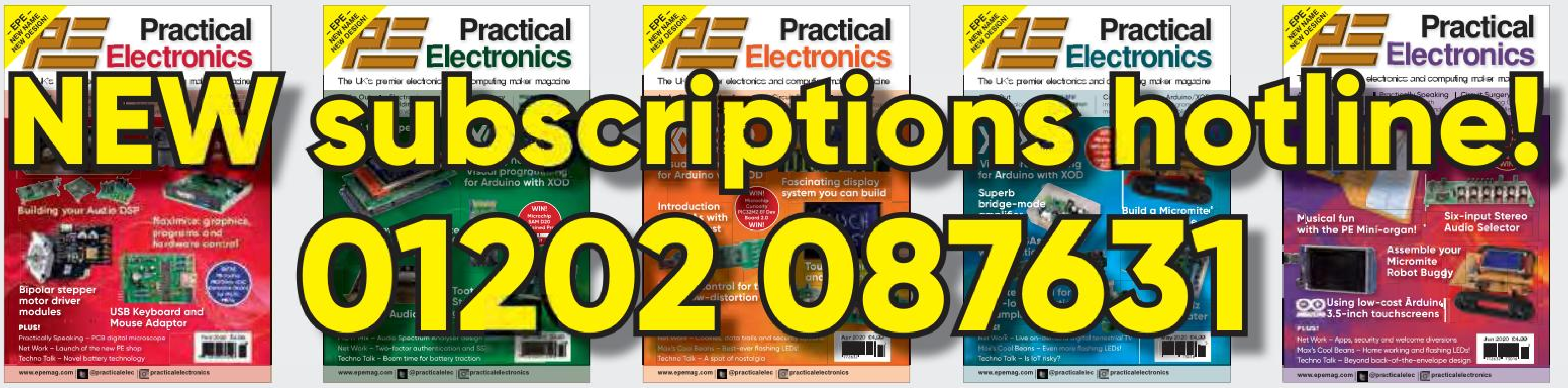

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Unfortunately, however, some delays in delivering your magazine are inevitable – here is a rough guide to the situation in late April.

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Matt Pulzer
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Practical Electronics

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Questions about articles or projects should be sent to the editor by email: pe@electronpublishing.com

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Probably the question I am most-often asked by readers is, 'how can I learn to use PICs?'. It's not an easy question to answer because PICs cover a huge range of devices. Nevertheless, I have always wanted to provide an easy-to-understand, comprehensive guide to using these vital devices.

Well, the big news in this issue is the start of a brand new series in *PIC n' Mix* devoted to mastering the PIC18 family of microcontrollers. You can read all about Mike Hibbett's plans for this hands-on educational project in this month's column.

The PIC18 family is made up of sophisticated 8-bit devices that offer flexibility, power and enormous interfacing opportunities. The series will teach you how to add Wi-Fi, USB and much more to PIC-based projects. I'm really looking forward to reading it, and I'm sure you will enjoy finding inspiration to build your own PIC18-based projects.

Calling PE Gemini builders

We recently received an email from reader Steve Moreham: 'Back in December 1970 I started building the *PE Gemini*, which I still have and want to get going again. Do you have the back issues? I do have some very tatty and faded photocopy pages (but incomplete). I built this amp as the issues came out when I had just started an electronics degree at Newcastle Poly.'

As always, Alan Winstanley, our *Net Work* guru / online editor / senior *PE* archivist came to the rescue, and we were able to send Steve a complete set of the five articles in PDF format. Are there any other *Gemini* builders out there who can offer some advice on building/running/tweaking this Hi-Fi pre-/power amp from 50 years ago? Just send me an email and I will be sure to pass on any assistance to Steve.

Keep well everyone

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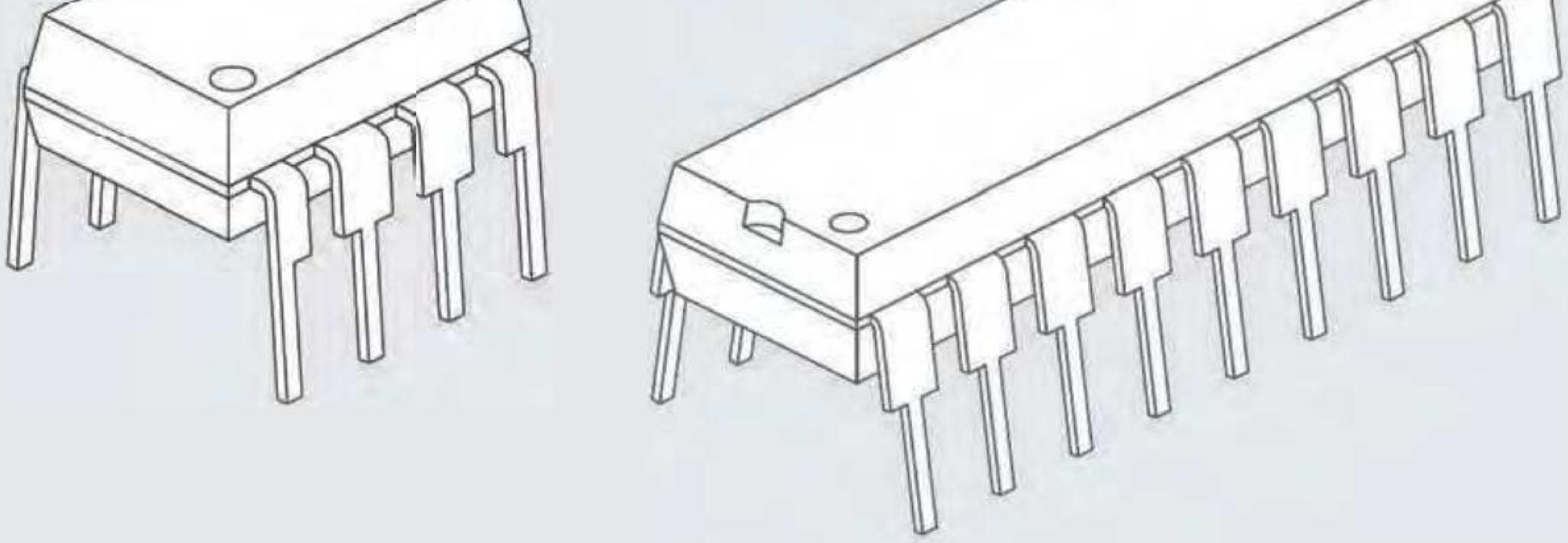

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Techno Talk

Silly stuff for the silly season

Mark Nelson

In these troubled times we all need a chuckle or two, so I thought we might examine some of the bizarre electronic products put on sale by some zany sellers. Or maybe they are deadly serious and it's their customers who are the outlandish ones. You be the judge while I entertain you with some playful teasing.

With high summer nearly upon us, how about some gardening ideas for electronicists? If that sounds crazy or off-topic, I invite you to consider a new twist to your 'practical electronics' hobby. It could even open your mind to a totally different outlook on 'mindfulness'. Back in 2018, a BBC television documentary broke the news that the Prince of Wales regularly communicated with the plants in his garden. 'I happily talk to the plants and trees, and listen to them,' explained Prince Charles, adding that talking to plants kept him 'relatively sane'. What the plants said back to him was not revealed – for obvious reasons – but now you can find out (in a manner of speaking).

I make the qualification, 'in a matter of speaking', because garden plants do not exactly speak, but 'sing' instead. Perhaps, disappointingly, they do not sing out loud in an audible kind of way (be grateful; you might not like their choice of music). Neverthless, you can now buy several different biofeedback devices that fully enable you to 'listen to the music of plants'. It's only a matter of time before someone reverse-engineers one of these gizmos and works up a DIY project for this magazine.

Sales pitch

Probably the slickest and glitziest sales pitch is that of Data Garden (**www.datagarden.org**), which invites you to 'connect to nature through sound' by way of its Plantwave technology. Plantwave uses electronic hardware that is paired wirelessly from a pot plant using a mobile app to translate biodata from plants into music played from your phone. The positively lush website explains that the company also makes immersive plant music installations for museums and festivals, produces interspecies concerts (pairing musical artists with plants) and leads guided meditation providing wellness services with plant music.

Even more ambitious is Music of the Plants (**www.musicoftheplants.com**), which uses high-conductivity electrodes connected to your favoured plant to drive a music synthesiser – offering a choice of root note (!) and a choice of scale (major, minor, harmonic minor, pentatonic, blues, Dorian, Phrygian, Lydian, healing, Japanese folk, Chinese, Damanhurian, Native American, Indian, Arabic, Persian or chromatic). Even better, their gadgets are encased in attractive bamboo-wood housings.

Another eco-friendly bamboo-wood gadget is Plants Play (**www.plantsplay.com**). Branded with the slogan 'Nature Live', this is a wearable device that allows you to listen to the music generated by plants and trees. Through two electrodes settled on the leaves, Plants Play converts electrical plant variations into musical notes, and sends them by Bluetooth on your smartphone.

Fundamentally similar is the Canadian PLANTchoir product (**https://plantchoir.com**), except this also allows you to record the music that your garden friends generate. Pitched for both domestic and business use, the product is promoted as being suitable for garden centres and floral shops, yoga and pilates studios, massage therapy studios, as well as acupuncture, chiropractic and other therapeutic settings. Other beneficiaries include day spas, medi-spas, nail and hair salons, together with day care, and Montessori and primary school establishments. Fabulous! But I must warn you that serene wellness comes at a price and you're looking at three-digit price tags.

Spoiler warning

Is this explosion of wellness for real or is it all a load of bovine byproduct? Thanks to the HowStuffWorks website, I can reveal it's utter tosh (**https://bit.ly/pe-jul20-dais**y). This sober assessment quotes plant physiologist Dr Monica Gagliano, associate professor in the School of Biological Sciences at the University of Western Australia, as saying: 'Simply put, the machines that translate the 'biofeedback' of plants into music have nothing scientific about them — the whole story has nothing to do with science or the sound of plants.'

For the techies among us, she adds: 'The apparatus used in many of these instances is a simple multimeter measuring the electrical impedance of the plant. The multimeter then transforms those electrical signals into notes using a sound chip, like those sound cards in your computer, which is how the sounds make sense to our human ears.' What a disappointing let-down!

Electrical spaghetti

More plant husbandry matters now, or maybe that should be more 'market garden' related than 'domestic back garden'. No matter – the subject is 'spaghetti' and as soon as anyone mentions spaghetti, my mind flits immediately to the superb BBC *Panorama* report on a bumper Swiss spaghetti harvest, narrated by the authoritative Richard Dimbleby (father of David and Jonathan). To see what I mean, take a peep at: **https://youtu.be/tVo_wkxH9dU** and only afterwards view **https://youtu.be/MEqp0x6ajGE**. You really must do this if you didn't see it when it was broadcast back in 1957.

Say the same word 'spaghetti' to many electronicists and they will reply: 'Oh yes, systoflex!'.This was a rather inflexible (and sticky!) kind of fabric tubing impregnated with something like shellac varnish that you used to slip over exposed wiring and component leads before far more flexible coloured neoprene or PVC plastic tubing replaced it. Dedicated restorers of vintage wireless receivers either use something similar made of polyester and sold by CPC as 'braided sleeving' or else buy shoelaces and remove the inner filling. But was its name systoflex or sistoflex?

Apparently both – according to the 15 January 1909 edition of *The Electrician* magazine, the firm of Spicer Brothers had just introduced its 'Sistoflex' trademarked product range of insulating materials, which subsequent advertisements mentioned as including flexible insulated tubing. However, the alternative spelling with a 'y' appears in British wireless magazines as early as 1926, so who made Systoflex and how did they get away with using such a similar-sounding name? I have no idea but maybe readers can come to the rescue!

Net Work

Alan Winstanley

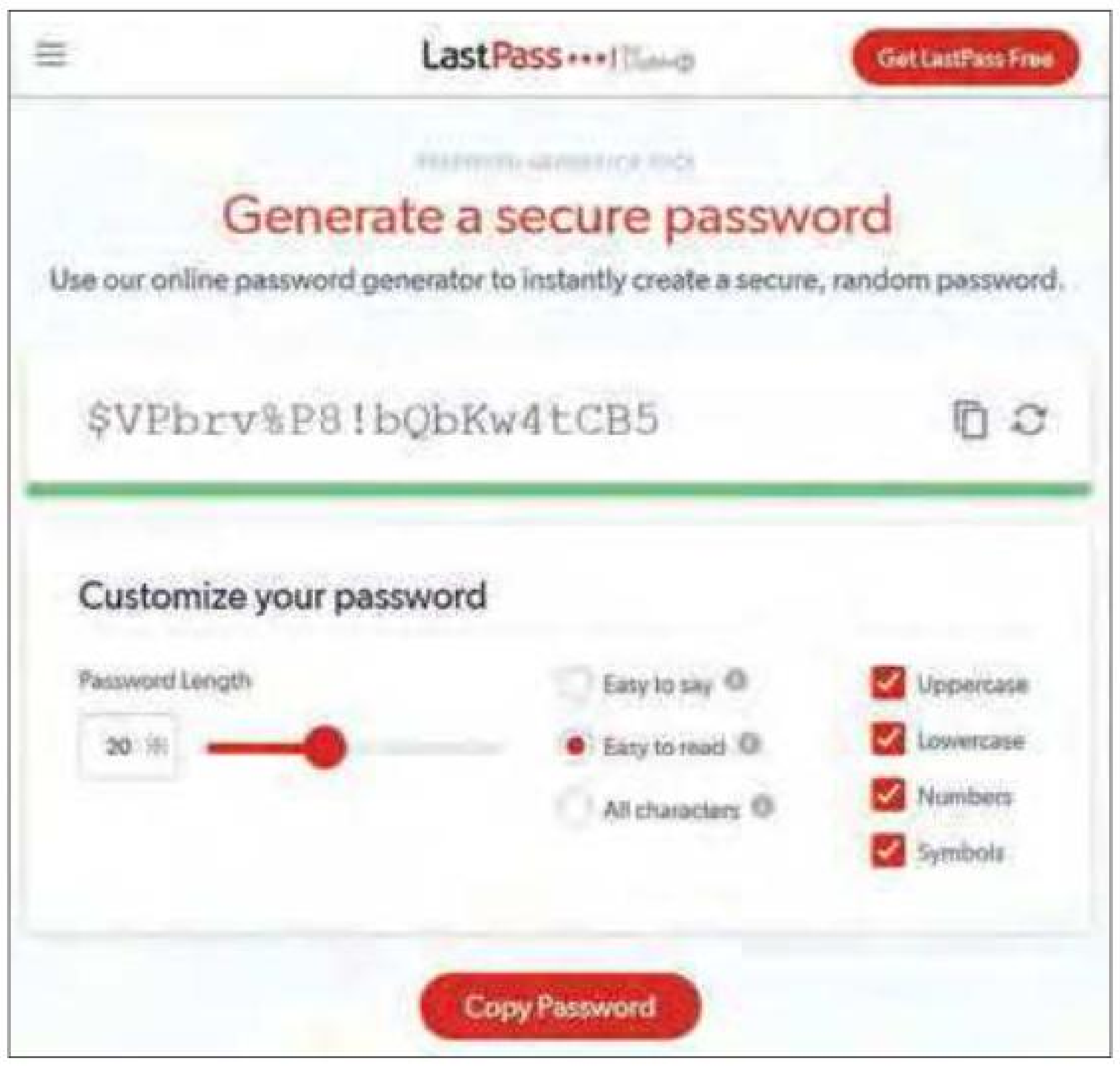
Online security is a never-ending quest for effectiveness and usability. This month, *Net Work* looks at choosing and setting up Two-Factor Authentication.

The British love their gardens, and so, during the recent isolation period, I found myself exploring my own and making a mental To-Do list of jobs to sort out in coming weeks. I discovered that my ancient lawnmower needed a new starter motor, and after earnestly surfing **eBay.com** (US) I found probably the last remaining Briggs & Stratton spare part anywhere in the world. Thanks to eBay's cross-border Global Shipping Program (facilitated by Pitney Bowes) it's heading from Ohio to the UK as I write; and checking the tracking data online whiles away the time during lockdown!

Protect your ID

Exploring the garden, I then spotted some litter snagged around a shrub: it was a carelessly discarded letter bearing someone's credit card details, with full name, address and account number laid bare for all to see. Only the 3-digit CVV (Card Verification Value) was missing, and in earlier days a less honest person could have treated themselves to a new lawnmower using this information.

In Britain, credit card security measures date back to the mid 1980s when 'space-age' holograms were introduced to prevent counterfeiting. Later, the 3-digit CVV was lasered into the signature strip to supposedly foil 'Cardholder Not Present' (CNP) scams. Recent new finance regulations (Strong Customer Authentication) have tightened up credit card security even more, in an ongoing drive to thwart credit card fraud. These new measures can force banks or credit card suppliers to authenticate the customer's identity via an SMS or phone call before a transaction can be completed.



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Online password generator provided by LastPass.

Last month's *Net Work* considered current trends in accessing online services more securely, especially the use of Two-Factor Authentication (2FA) which introduces an extra step to confirm a user ID. The vast majority of websites currently rely on username and password combinations ('credentials') when logging into an online account, but the risk of having personal data stolen from insecure websites, or hijacked by malware, means the risks of impersonation and fraud are ever present.

More than 90% of us know not to use the same or similar passwords on multiple websites, but 66% of us do anyway, says LogMeIn in their 2020 *Psychology of Passwords* report. Instead, try creating one specific to that website and mix in a symbol or two to make life a bit harder for hackers, or create a strong passphrase, or try the online password creator at **www.lastpass.com/password-generator**. If ever a 'leaked' or stolen password comes to light, at least you would know its source. The website **https://haveibeenpwned.com** is probably the best online resource for checking whether your logins have been stolen in the past. (If ever you wondered, 'pwned' is slang for 'owned' or 'taken over' after a games programmer once mistyped the letter 'o'; the typo entered everyday culture).

Safeguarding logins

When surfing online, the major web browsers will offer to store website passwords securely. The latest version of Firefox (v.76) can also check for breached websites and compromised passwords, reporting this in its built-in password manager (Firefox Lockwise – type `about:logins` to see). A forthcoming Firefox tool called Private Relay can also create a disposable (or 'burner') email alias during signing up, shielding your real address from prying eyes as a further safeguard.

To help manage multitudes of logins, dedicated password manager programs can encrypt and store credentials either on disk or in the cloud, so next I'll summarise some popular ones. Regular readers will recall my choice of Roboform, which offers both local and cloud options. Its portable USB memory key version (Roboform2Go) has been dropped, citing increasing problems attaching the Roboform plug-in to browsers. However, Roboform Free 8.6.7 now offers unlimited login storage for a dedicated Windows or Mac machine: it encrypts and stores logins on your local disk and is worth trying on a busy machine. It can also store data from fill-in web forms (handy for complex or tiresome ones that you use regularly) as well as creating complex passwords. Roboform Everywhere is the regular paid-for cloud version that can be used across all your devices. Available for download from: **www.roboform.com**

Keepass is a free open-source password manager for Windows and Linux (Wine), also offering a portable USB version. It is extensible through plugins. When tested, it made a decent job of importing CSV files from Roboform after mapping the data fields, and I liked the 'Emergency Sheet' printout idea. There are lots of options for advanced users to play with, but I found it less seamless to use than Roboform. Download the latest free version 2.44 from: **https://keepass.info**

Password Safe for Windows (**https://pwsafe.org/**) creates a single password-protected master list of all your logins. It can also support Yubikey's USB authenticators (see *Net Work* last month), requiring both a Yubikey and a master password to access stored passwords. Autofill will usually complete a login automatically, and this can be reprogrammed using codes. It's maintained by volunteers, and is probably best suited to proficient computer users. PasswordSafe2Go stores passwords on a disk-on-key instead, and costs about £10 via Digital River.

LastPass password management apps help users to handle log-ins across all their devices.

LogMeIn offers LastPass for consumers with free and paid-for ($36/$48 per year) versions, and they can be used on all your devices. It relies on a master password and supports multi-factor authentication. A password generator is included and browser extensions and mobile apps are available. See **www.lastpass.com** for details. LogMeIn is also the home of GoToMyPC remote accessing software and enterprise engagement tools. Rival Dashlane is another well-known cloud-based service: a free version stores 50 logins on one device. Subscriptions are available from: **www.dashlane.com**

1Password has apps for Mac, iOS, Windows, Android, Linux, and Chrome OS. A master password protects your (encrypted) password database and it also supports limited 2FA. It costs from $36 to $60 a year and a free trial is available from: **https://1password.com**

Sorting out SIM-swapping

As described in last month's column, 2FA is available to safeguard access to many key web services. Normally, a One-Time Passcode (OTP) such as a PIN is sent via SMS to confirm one's identity. Opinions vary about how robust this method actually is, because in theory sophisticated fraudsters could trick a cellphone operator into transferring your own cellphone number over to a SIM card in their possession, a fraud known as SIM-swapping. Then they could intercept SMS messages and hack into online accounts. In April, Britain's consumer watchdog *Which?* stated that reports of SIM-swapping had leapt by 400% since 2015. UK cellphone operators have tightened up protocols to prevent fraud, but the system is still not perfect. You can read the report from *Which?* at: **https://bit.ly/pe-jul20-which**

Which? recommends removing your phone number from any websites that use it to reset passwords, and use 2FA authenticator apps instead; they are embedded in your physical device so they circumvent SMS messaging entirely. The free Microsoft Authenticator app uses OTP and is available for Android and iOS. Apart from Microsoft accounts it will also work with Google, Amazon, Instagram, Netflix and others. The app can be installed from Google Play or App Store (more details are at: **https://tinyurl.com/ycxgnqsn**) The Google Authenticator app plays a similar role for Google account holders.

Another highly popular authenticator app is Authy (**https://authy.com**) from Twilio, which has an extra free desktop version for Mac, Windows and Linux fans. Its designers stress that Authy can replace Google Authenticator, and it works across multiple devices. It can easily capture 2FA QR codes from Facebook, Amazon, Google, Microsoft, Dropbox and many more. Google de-emphasises other 2FA apps in favour of Google Authenticator: 'If any websites prompt you to use Google Authenticator for 2FA, note that you can always substitute the Authy 2FA app instead. Although they work in similar ways, Authy is more feature-rich and allows for multi-device syncing, cloud-backups, and easier account recovery should you change or lose your phone or device', the developers claim; a blog at: **https://tinyurl.com/y874u5nj** compares Authy with Google Authenticator. If you are Google and Microsoft-averse, then Authy is probably the authenticator app to choose. Its online support and step-by-step instructions seem excellent.

Dipping into 2FA

Choosing an authenticator app is only half the battle, though: 2FA has to be enabled in your accounts as well, which can be an onerous and time-consuming task involving some unintuitive and arcane security settings. To set up Authy with a Google account for example, log into **https://myaccount.google.com** then go to Security settings. The option of what Google cheekily dubs access by 'Less secure access apps' is disabled by default: it needs enabling manually for Authy to work. To activate Authy requires 'App Passwords' to be enabled which I found to be a convoluted procedure. For more details of setting up App Passwords, see: **https://support.google.com/accounts/answer/185833**

The technology is still evolving, both for users and online operators, and when disappearing down the rabbit hole of implementing 2FA for the first time, the learning curve can be frustrating. Other considerations to investigate include unforeseen 'gotchas' when, for example, a phone breaks or is stolen, or apps have to be reinstalled and logins are lost, or users find themselves locked out of their accounts altogether. Then what? Presently, there is perhaps a slight distrust of 2FA implementation itself: 'Use Authy instead and don't worry about losing all your accounts' said one dismayed Google app reviewer.

So-called hardware tokens such as the Yubico USB Security Keys are another option – simply touch the key plugged into your device to verify your ID. Yubico has sent some samples for me to test on some live accounts – I'll update readers next month.

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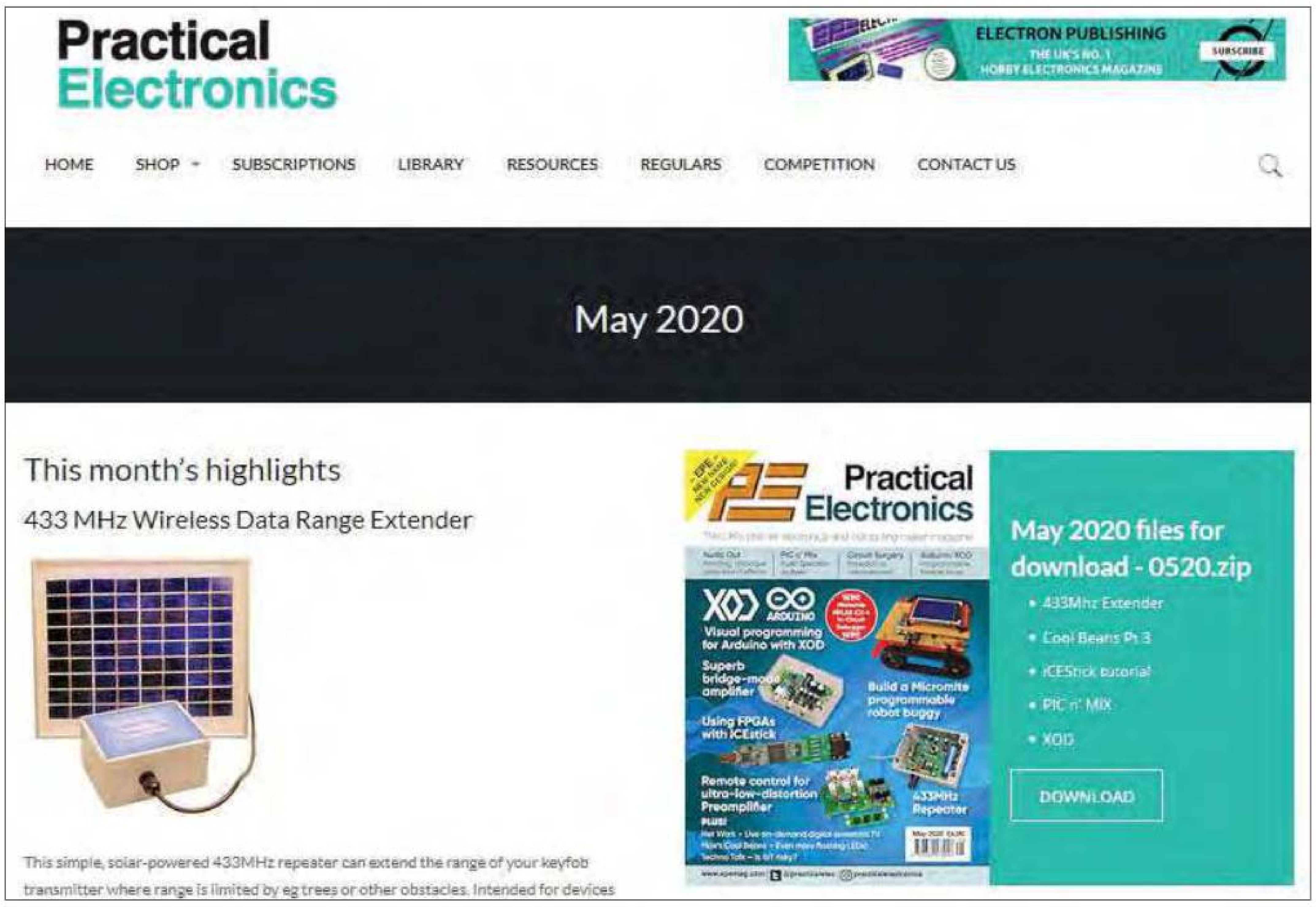

May 2020

This month's highlights

433 MHz Wireless Data Range Extender

This simple, solar-powered 433MHz repeater can extend the range of your keyfob transmitter where range is limited by eg trees or other obstacles. Intended for devices

May 2020 files for download - 0520.zip

- 433Mhz Extender
- Cool Beans Pt 3
- iCEStick tutorial
- PIC n' MIX
- XOD

DOWNLOAD

How monthly updates will look on the new *PE* website: the 'Download' button under the cover shot links to source code files for that issue.

Space roundup

A new type of recovery satellite – the Mission Extension Vehicle (MEV) – developed for NASA by Northrop Grumman recently accomplished a remarkable first in commercial space technology by docking with an orbiting satellite that was running low on fuel. MEV-1 successfully latched onto a 20-year-old satellite in order to orientate and propel it for a further five years before it is finally decommissioned. The MEV will then attach itself to another orbiting satellite(!).The space-age tow truck is compatible with 80% of orbiting geostationary satellites and has a life span of 15 years, says NASA.

NASA has awarded contracts to build a new human landing system (HLS) to take the first woman and another man to the moon, prior to advancing towards Mars. SpaceX, owned by Elon Musk, Blue Origin, owned by Jeff Bezos (see March 2020 column) and technology firm Dynetics have each been awarded contracts for the HLS. More about NASA's moon shot at: **https://go.nasa.gov/2B4pVmr**

SpaceX launched its seventh array of Starlink satellites at the end of April in its quest to stream low-latency Internet data down through a constellation of satellites. More than 420 Starlinks are now in low-earth orbit, launched using reusable rockets. A number of apps are available that allow interested observers to track satellite trails that are sometimes visible with the naked eye – try **findstarlink.com** (conditions and sun permitting), or the Satflare website at: **https://bit.ly/pe-jul20-sat**

App developer Terminal Eleven offers an excellent augmented reality (AR) app called SkyView which uses the camera and GPS to locate and identify stars, planets, constellations, satellites and more besides. It's a low-cost, good value app; seeing it listed in Google Play Store the author ran it successfully on an Android phone but could not install it on a larger Android tablet. Terminal Eleven didn't respond to queries when asked why.

The UK plans to implement its new Digital Services Tax from 1 April, levying 2% on social media, search and online marketplaces that derive profit from UK users. Other countries are following suit, but the UK rate is the lowest, as reported on: **https://taxfoundation.org/digital-tax-europe-2020**

The US previously threatened retaliation, but an OECD-brokered tax code, addressing the issue of multi-nationals shifting profits around to evade local taxes, is still awaited.

Last, more news of the PE website: with our new shopping cart now in full swing, details of legacy projects from the past ten years have now been imported successfully and will be online by the time you read this. You can also sign up to download the corresponding month's source code (.zip) file directly into your shopping cart, free of charge, and it will also be saved in your account for future reference. We regret that legacy PCB PDF files from the very oldest projects (2007 – 2012) are considered obsolete and will no longer be available online. Our website URLs will be configured to automatically forward users to the new website as a matter of course.

See you next month for more *Net Work!*

The author can be reached at:
alan@epemag.net

Practical Electronics

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JUNE 2020

PROJECTS • AM/FM/CW Scanning HF/VHF RF Signal Generator – Part 1 • Low-cost 3.5-inch touchscreen for the Arduino or Micromite • Ultra-low-distortion Preamplifier with Tone Controls – Part 3

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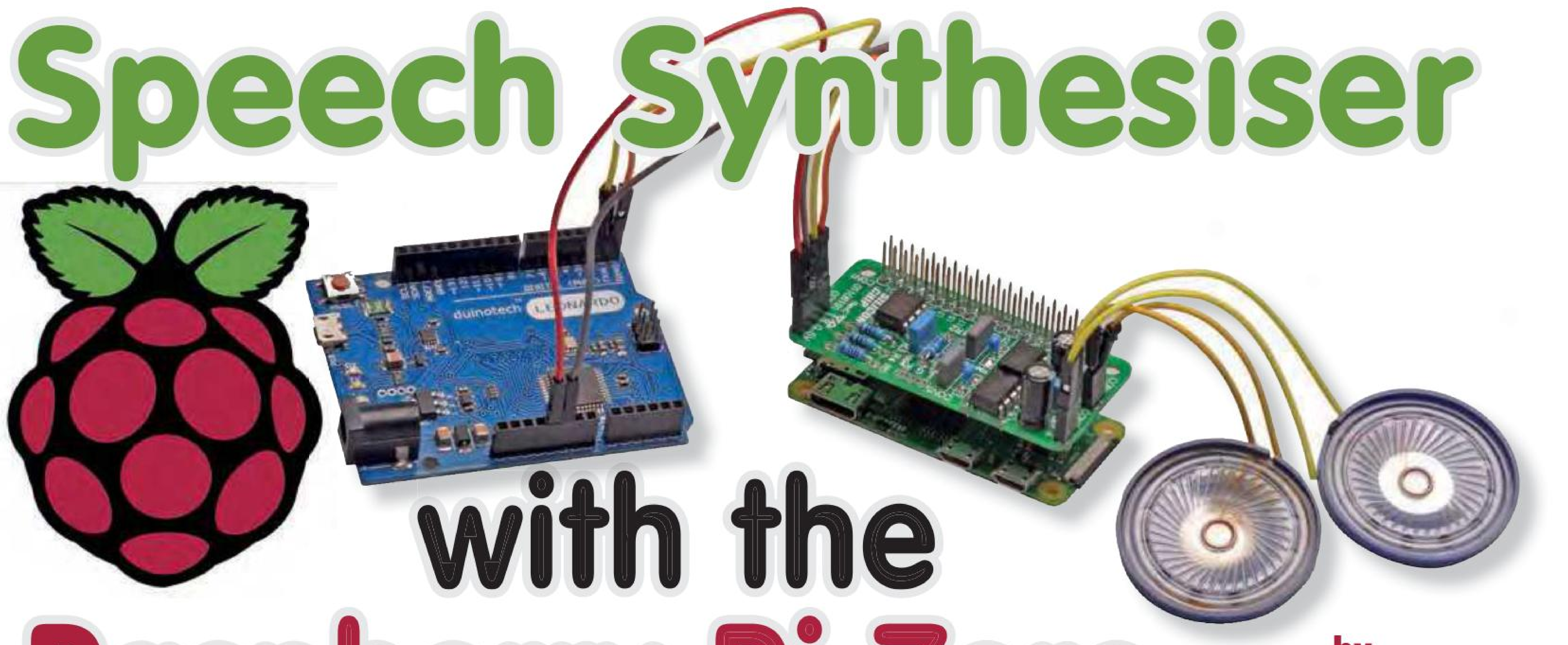
Speech Synthesiser with the Raspberry Pi Zero



Shown above: the completed Speech Synthesiser consists of a small PCB fitted to a Raspberry Pi Zero board, and measures only 65mm by 31mm and is capable of directly driving a small pair of stereo speakers. We show it here connected to a Arduino board, although any microcontroller or computer which provides a serial interface can be used to control the Speech Synthesiser.

by
Tim Blythman

Most electronic devices communicate with us via blinking lights. But humans use speech to communicate virtually any concept easily and clearly. So wouldn't it be better if your electronic gadgets spoke to you? Now you can make them do just that, with a low-cost Raspberry Pi and our simple hardware and software, in just about any language. They can even play music!

We have published several projects over the years which can be used to play back sounds, and many of these can be (and have been) used to play back recorded voice samples to indicate to a user what is going on inside an electronic device.

But you're usually limited to just a handful of voice samples, restricting the information that you can convey with such devices.

Not so with this one, which can generate a virtually unlimited number of different phrases, short or long. They broadcast clearly, in the language of your choice, and with the option of several different accents.

You just need to feed in text over a serial port (eg, from just about any microcontroller or computer), and it will be translated into sound.

These days, pretty much every portable electronic device (and some which are intended to be placed around the home) can speak to users.

We wanted to be able to add that capability to any microcontroller-based project in a compact and low-cost package, and that is what we have achieved.

Various speech options

Single-chip 'speech solutions' do exist; for example, the SpeakJet at: **www.magnevation.com**

While capable of generating speech and other sound effects, it still requires an external filter and amplifier.

The SpeakJet IC costs aroun £20, and while impressive in what it does for its size, we think our solution is competitive on cost and versatility, even if it is slightly larger.

We've also seen an Arduino speech shield, closer to £50 in cost, which is more expensive than our solution and also larger.

Enter the Raspberry Pi Zero

These days, the Raspberry Pi 3B+ can be bought for around £34 plus postage from several resellers (eg, **https://thepihut.com**). But the Pi 3B+ is overkill for what we need.

So we've turned to a smaller relative, the Raspberry Pi Zero. Remarkably, the Raspberry Pi Zero can be had for under £5 from PiHut.

It is actually a small form-factor variant of the earlier Raspberry Pi Model B, but the Raspberry Pi Zero lacks features such as Wi-Fi or even a headphone socket.

The Pi Zero W adds Wi-Fi, and there is also the Pi Zero WH, which adds Wi-Fi and soldered headers to the mix. It retails for around £13, over twice the cost of the basic Pi Zero. However, all of these choices are excellent value for money.

To turn our Pi Zero (of whatever flavour) into a *Speech Synthesiser*, we need to get audio out and amplify it. For this, we've created a small DAC and amplifier board to provide direct stereo speaker drive.

Our DAC/amplifier board is the same shape as a Raspberry Pi Zero and sits directly above it. You'll also need some speakers and a microSD card to create a finished, working *Speech Synthesiser*, as well as some means of supplying serial commands to the completed unit, so it knows what to say.

Advanced users could even program the Raspberry Pi directly in a language such as Python, but you would need to be reasonably confident using a Linux command line. We have also provided some code to allow an Arduino board to control the *Speech Synthesiser*.

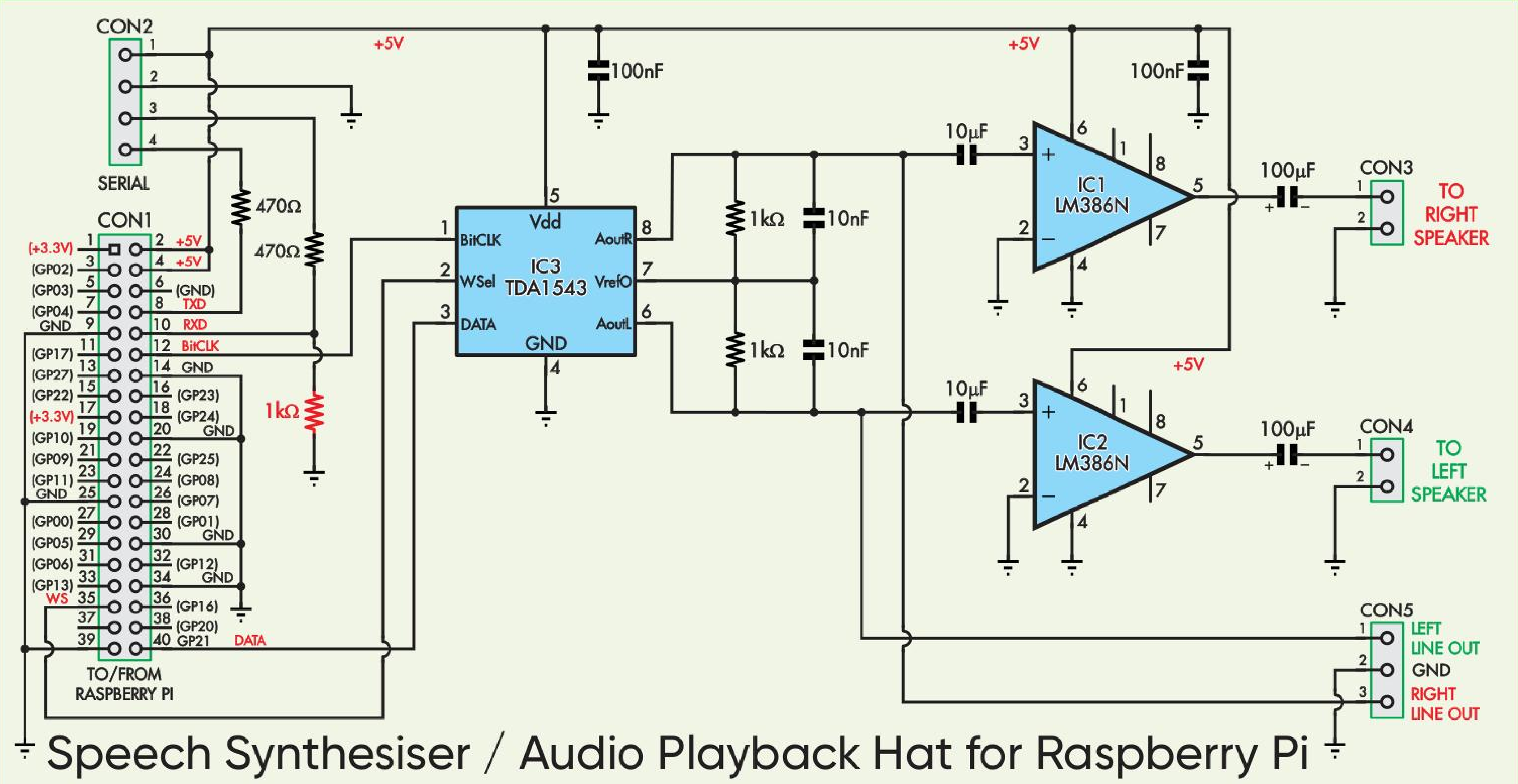

CON2
1
2
3
4
SERIAL
+5V
100nF
+5V
100nF
470Ω
470Ω
1kΩ
CON1
(+3.3V) 1
2 +5V
(GP02) 3
4 +5V
(GP03) 5
6 (GND)
(GP04) 7
8 TXD
GND 9
10 RXD
(GP17) 11
12 BitCLK
(GP27) 13
14 GND
(GP22) 15
16 (GP23)
(+3.3V) 17
18 (GP24)
(GP10) 19
20 GND
(GP09) 21
22 (GP25)
(GP11) 23
24 (GP08)
GND 25
26 (GP07)
(GP00) 27
28 (GP01)
(GP05) 29
30 GND
(GP06) 31
32 (GP12)
(GP13) 33
34 GND
WS 35
36 (GP16)
37
38 (GP20)
39
40 GP21
DATA
TO/FROM RASPBERRY PI
IC3 TDA1543
Vdd
BitCLK
WSel
DATA
AoutR
VrefO
AoutL
GND
1kΩ
10nF
1kΩ
10nF
10µF
10µF
IC1 LM386N
IC2 LM386N
+5V
100µF
100µF
CON3
TO RIGHT SPEAKER
CON4
TO LEFT SPEAKER
CON5
LEFT LINE OUT
GND
RIGHT LINE OUT
Speech Synthesiser / Audio Playback Hat for Raspberry Pi

Fig.1: the circuit of the Raspberry Pi hat which adds the ability to drive two speakers. It can be used for speech synthesis or general audio playback. Audio data comes from the Pi via header socket CON1 in I^{2}S digital format and is fed to DAC IC3. The analogue audio signals are then coupled to amplifiers IC1 and IC2 and on to headers CON3 and CON4, which connect to the speaker(s). The resistor shown in red is left off for 3.3V signal levels on CON2.

Why try Pi?

The Raspberry Pi series of single-board computers are astonishingly cheap for what they are, and this project would work with any current variant of the Raspberry Pi.

The larger models will result in a less compact finished product, but would provide a great way to experiment with speech synthesis before committing to buying another, smaller Pi.

The speech synthesis software we are going to use is an open-source project called 'espeak-ng', see: **https://github.com/espeak-ng/espeak-ng**

The nice thing about espeak-ng is that it includes many different languages and voices, so it is perfect if you need speech in English or just about any other language. You can download variants of espeak-ng for different operating systems, such as Windows, if you would like to hear what it sounds like first. You can find these downloads at: **https://github.com/espeak-ng/espeak-ng/releases**

Since the Pi Zero is capable of running a wide range of advanced software, we've included some extra features in our *Speech Synthesiser*.

We've also included another open-source program, 'madplay', just visit: **https://sourceforge.net/projects/mad/files/madplay/**

It can decode and play MP3 files, so if you also want to use your *Speech Synthesise* as a simple sound-effects module, you can do that.

If you have one of the Wi-Fi-enabled Pi variants, the *Speech Synthesiser* can also become a very simple internet radio. Instead of playing a file, madplay can decode and play an internet radio station using a single command.

We developed the software for this project using a Raspberry Pi WH, as the Wi-Fi allowed us to download the necessary software packages directly from the Internet. This also lets us use SSH (secure shell) via Wi-Fi to tweak our settings remotely.

So while the Pi Zero is the cheapest option, and requires the least power to operate, you do give up some interesting possibilities compared to the Wi-Fi-enabled variants.

Hardware overview

The *Speech Synthesiser* consists of a few parts, primarily the Raspberry Pi itself, plus a 'hat' that we have designed, which plugs into it and allows it to drive one or two speakers.

This is necessary because the Raspberry Pi Zero does not have any onboard analogue audio outputs.

The circuit for this 'hat' is shown in Fig.1. It connects to the pin header of the Raspberry Pi via CON1, a 2x20 pin socket. CON2 is a 4-pin header which makes the 5V supply from the Raspberry Pi available (eg, to power an Arduino board or similar), plus a 2-wire serial interface for control.

The three resistors between CON2 and CON1 allow a 5V device like an Arduino to communicate with the Raspberry Pi's serial port, which operates at 3.3V.

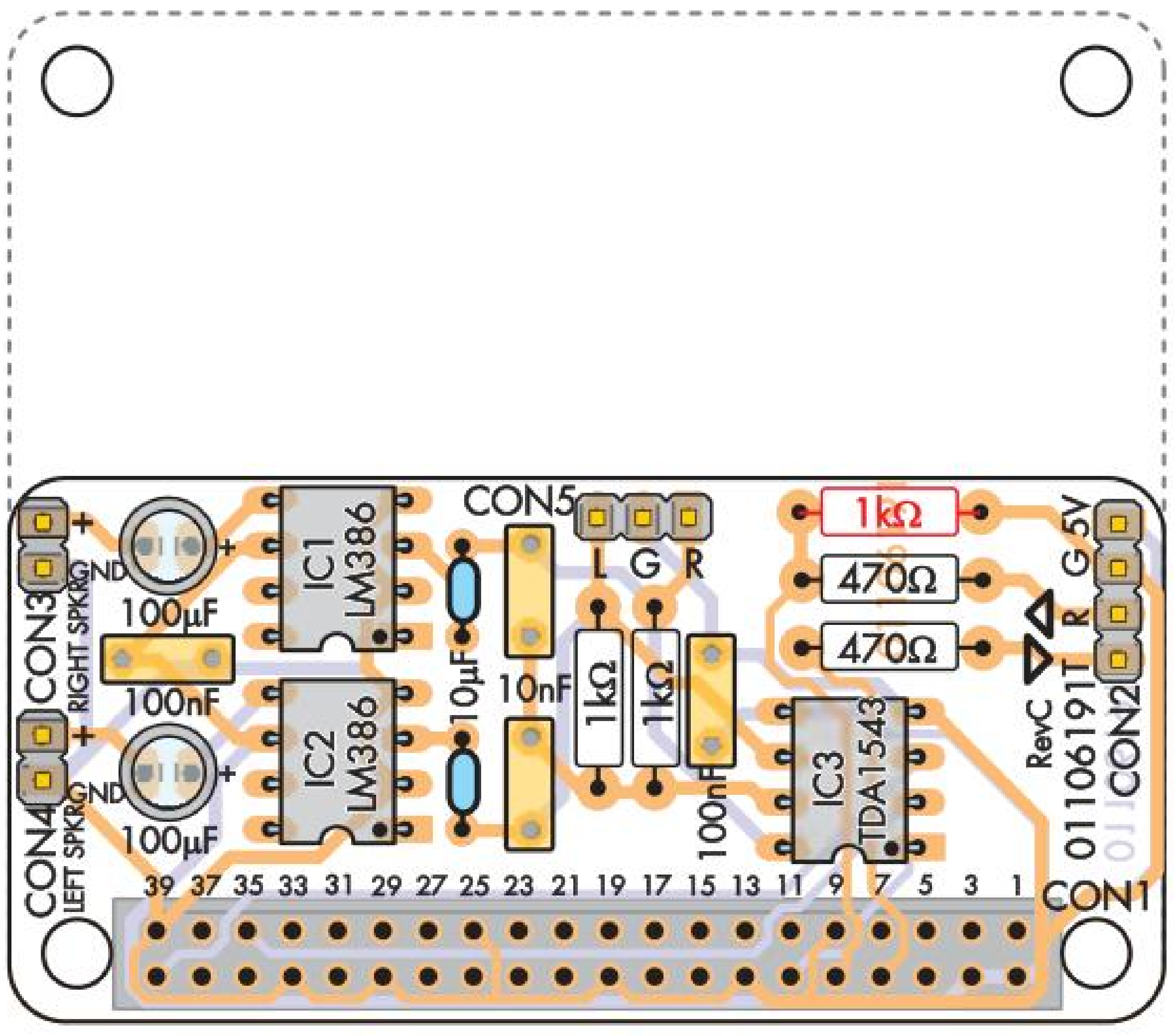
If you will be controlling the *Speech Synthesiser* from a 3.3V micro board or similar, then you should replace the two 470Ω resistors with wire links (or fit them anyway, it won't matter) and omit the 1kΩ resistor to disable the voltage conversion.

This UART serial port is the primary means of control and communication between the external microcontroller and the Raspberry Pi microcomputer, which handles all the speech synthesis and audio playback tasks. IC3 is a TDA1543 16-bit digital-to-analogue converter (DAC). It is fed digital audio data, in I^{2}S format, from the Raspberry Pi on pins 12, 35 and 40 of CON1. These are the bit clock, word clock and serial data pins respectively. Pins 6 and 8 of IC3 are the analogue audio outputs, which act as current sinks.

The current flow is proportional to the desired audio signal voltage levels for the two stereo channels.

These currents are converted into voltages by the two 1kΩ resistors connected between those pins and the voltage reference output, pin 7, which sits at around 2.2V and can supply up to 2.5mA.

DAC switching artefacts are attenuated by filtering from the 10nF capacitors across these resistors. The resulting voltage signals are coupled to the non-inverting inputs of audio amplifiers IC1 and IC2 via 10µF non-polarised capacitors. IC1 and IC2 are LM386 amplifiers which need few external components.



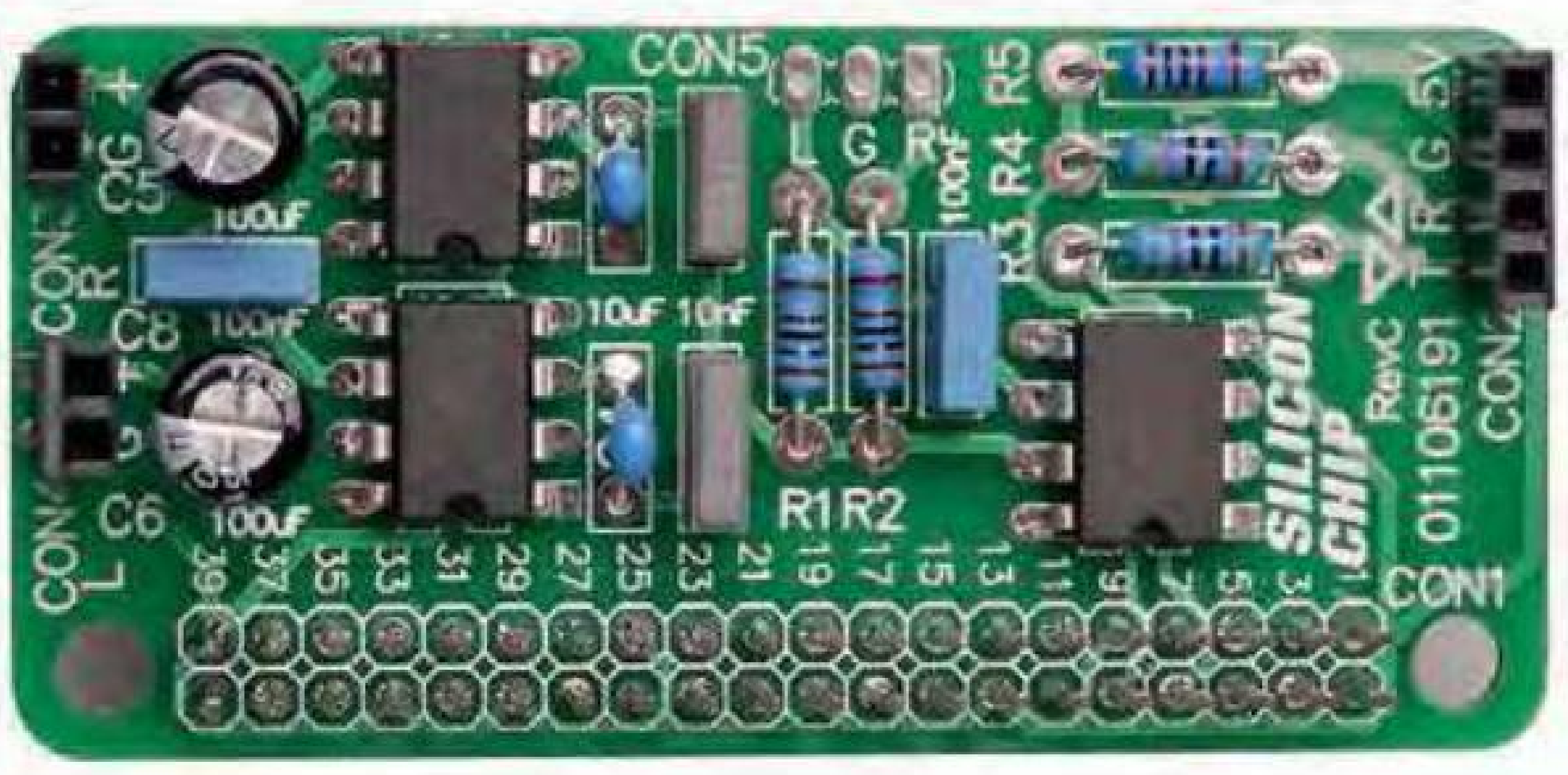


Fig.2: the Pi audio hat is quite compact and easy to build, with relatively few components. Take care with the orientation of the ICs and electrolytic capacitors. CON1 is mounted on the underside and plugs into the GPIO header on the Raspberry Pi host. CON2 is for serial communications. The resistor shown in red is left off for 3.3V signal levels on CON2. Speaker wires could be soldered directly to the board, rather than fitting headers CON3 and CON4. The dotted outline at left shows the size of the regular Raspberry Pi PCB, giving an idea of how the board would fit on one.

Their 5V supply from the Raspberry Pi is bypassed by a shared 100nF capacitor. Their outputs are AC coupled to the speaker terminals, CON3 and CON4, by a pair of 100µF electrolytic capacitors which remove the DC bias in the signal. This is provided by IC1 and IC2, to keep the signals within their supply rails.

With pins 1 and 8 of IC1 and IC2 left open, each amplifier provides a voltage gain of 20. They can both deliver around 250mW into an 8Ω load.

The line-level signals are fed separately to pin header CON5 in case you need to feed them elsewhere, but keep in mind that these signals are not ground-referenced, but instead have a DC bias of around 1V.

Software

The software for this project can be downloaded from the July 2020 page of the *PE* website. This is a large download, around 400MB because the software is supplied as a complete installation of the Raspbian Lite operating system, with some extra packages and settings incorporated.

Raspbian Lite dispenses with the graphical user interface normally included with Raspian, reducing the install size (and therefore download size) substantially.

You can fit the software on a 2GB microSD card, although larger cards can be used. You can either write our supplied image directly to your card, or follow the instructions below to set up the operating system in a step-by-step fashion. The step-by-step method is more involved and requires a bit more knowledge of the Linux command line.

One disadvantage of using our 2GB image is that your file system will be limited to 2GB, even if you use a larger card, and much of the space is already taken up by the operating system.

If you need more than 2GB (eg, you want to store a large number of audio files on the card), then you should use the step-by-step process and a higher-capacity card.

The step-by-step approach is also best if you wish to customise your setup, but note that you will need a Raspberry Pi variant with Wi-Fi to download the packages.

As noted above, we're using espeak-ng and madplay to provide the audio functions. We also need to apply some custom settings to enable the UART serial control interface and the I^{2}S (digital audio) interface. Plus, if you're using a Wi-Fi-enabled variant, it's necessary to set up the Wi-Fi interface.

We're also configuring the Pi to boot from the microSD card in a read-only mode. This allows us to simply remove power when we're finished with the unit, rather than having to send a serial command to perform a 'clean shutdown', as would be necessary if the card was writeable during use.

This does not permanently make the card read-only, as you can easily add a jumper to enable write access temporarily.

Building the DAC and amplifier board

The DAC/amplifier 'hat' board is a handy little device that can be fitted to any variant of the Raspberry Pi. Use the PCB overlay diagram, Fig.2, as a guide during construction.

Start by fitting the resistors. As mentioned earlier, leave out the 1kΩ resistor at upper-right if you will be controlling the Raspberry Pi from a microcontroller that has 3.3V I/O levels.

Follow with the ICs, which can either be soldered directly to the board or plugged into sockets. Regardless, ensure they are oriented correctly, with their pin 1 indicators towards the bottom of the board, as shown in Fig.2.

Next are the MKT and ceramic capacitors, which are not polarised, then the electrolytic capacitors, which are. Their longer leads indicate the positive end and this must face towards the right side of the board, as shown by the '+' signs on the overlay diagram and PCB itself.

The stripe on the capacitor cans indicates the negative end and so should face away from the '+' signs.

Finally, fit the pin headers, with the 2x20 pin socket mounted on the underside of the board as shown. You might like to plug it into the Raspberry Pi board before soldering it, to ensure it sits correctly.

You could use a stackable header here, which would be useful if you plan to connect any of the other Raspberry Pi I/O or supply pins to external circuitry (other than the serial port, which is already wired to CON2 for you).

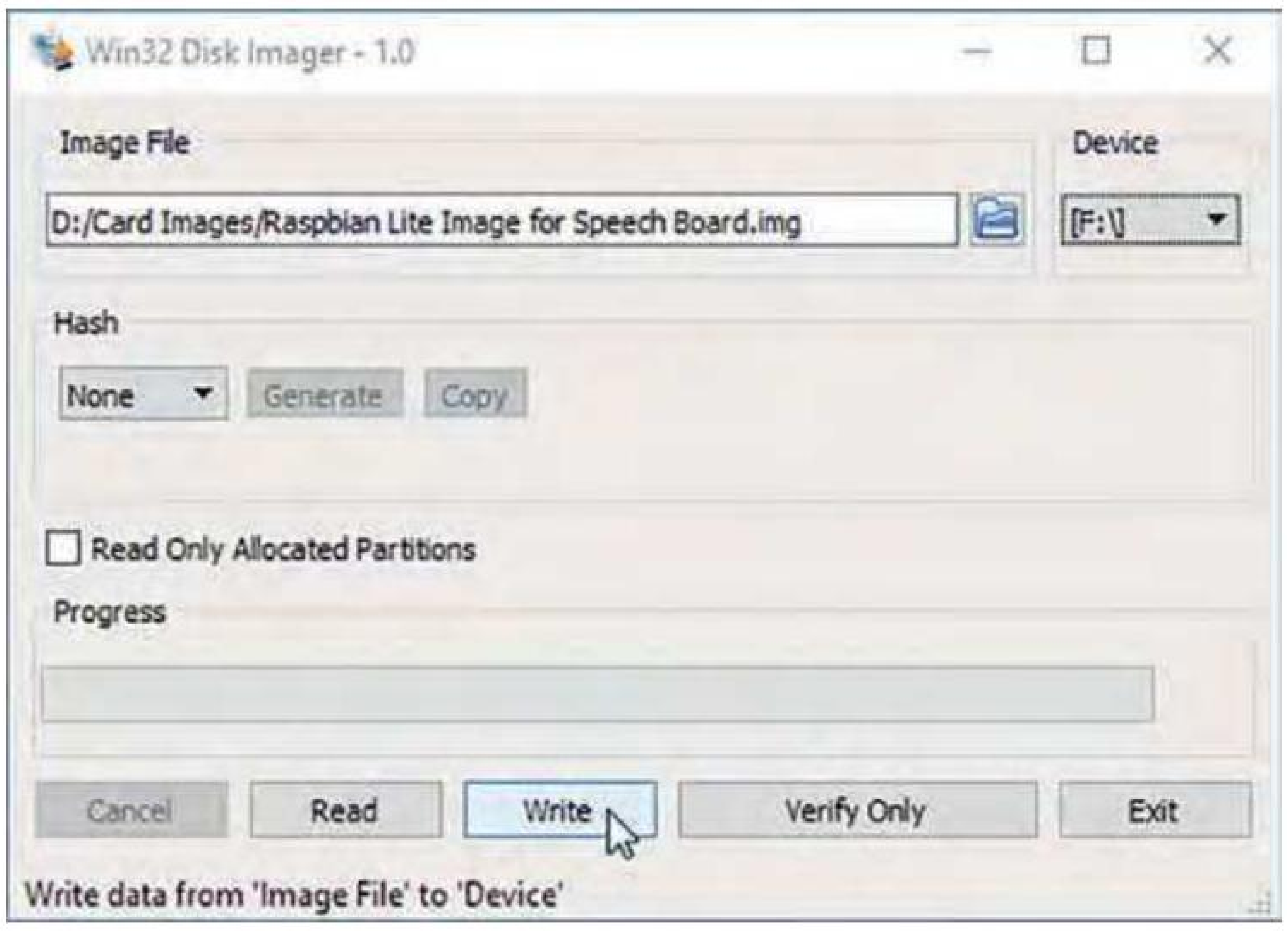

Win32 Disk Imager - 1.0

Image File: D:/Card Images/Raspbian Lite Image for Speech Board.img

Device: [F:\]

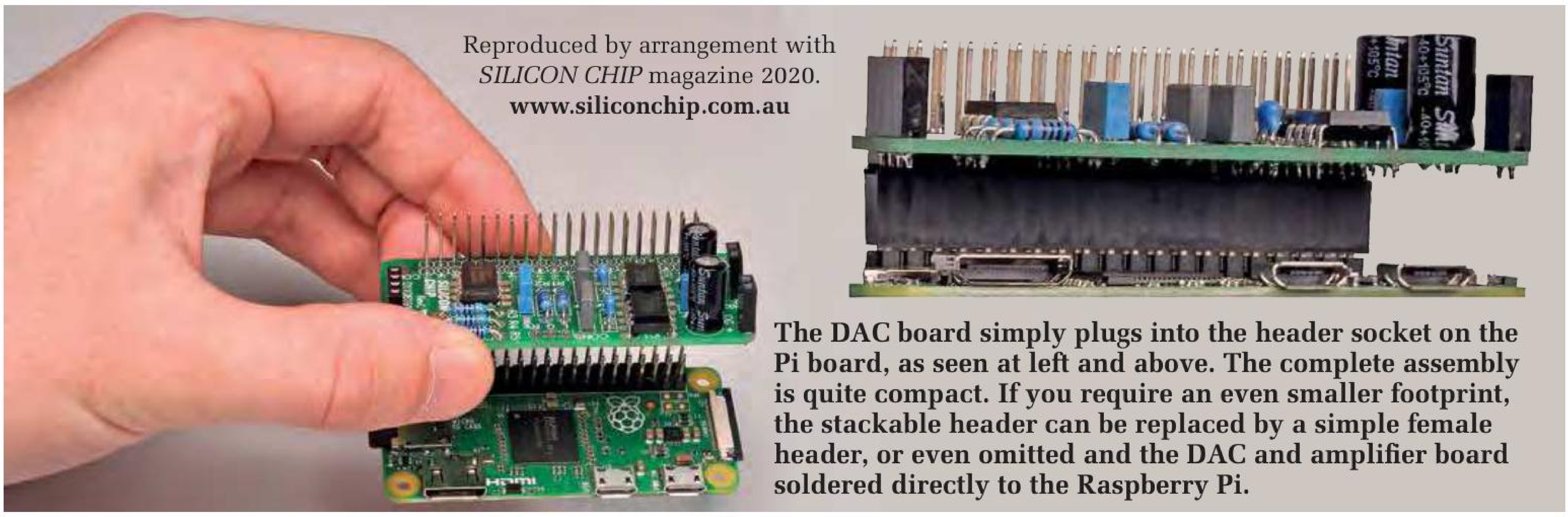
Hash: None

☐ Read Only Allocated Partitions

Progress

Write data from 'Image File' to 'Device'

Fig.3: Win32disk-imagewriter is a Windows program used to write the Pi software to the microSD card. You can start with our pre-configured image, or a basic Raspbian Lite installation if you are customising your software. Take great care using Win32 diskimagewriter, as it can overwrite your data if used incorrectly.



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The DAC board simply plugs into the header socket on the Pi board, as seen at left and above. The complete assembly is quite compact. If you require an even smaller footprint, the stackable header can be replaced by a simple female header, or even omitted and the DAC and amplifier board soldered directly to the Raspberry Pi.

Alternatively, you could dispense with CON1 entirely and solder the hat directly to the Pi. But if you do this, take care that the underside of the DAC and amplifier board does not touch the top of the Pi. You may like to slide a strip of plastic or insulating card between the two to ensure separation.

Keep in mind that you will need access to the microSD card slot. 5V DC power can be fed to the Pi through CON2 if necessary.

Similarly, you could solder wires directly to the speakers rather than fit headers for CON3 and CON4. Once the board is complete, plug it into the Raspberry Pi, and you are ready to install the software.

Simple software setup

The simplest way to set up the software for the *Speech Synthesiser* is to download our firmware image. This is a .img file which has been put into a .zip archive to make it smaller. The .img file is a byte for byte 'snapshot' of the SD card.

Unfortunately, that means it's not possible to do a simple copy and paste, as the file needs to overwrite everything including the existing file system on the card.

So we need to use a program called Win32diskimagewriter to write the image to the SD card. Win32diskimagewriter is written to work on Windows computers and can be downloaded from: **https://sourceforge.net/projects/win32diskimager/**

If you have a different operating system, then alternatives such as Etcher (**www.balena.io/etcher**) or the 'dd' command under Linux perform the same task. Other programs will have their own instructions for writing images to cards.

Connect the microSD card to your PC; if your computer does not have a card slot, use a USB card reader/writer (eg, Jaycar Cat XC4740). Install Win32diskimagewriter and open it.

Extract the .img file from the .zip file and click on the folder icon under 'Image File' to select the image file. Double check that the 'Device' setting matches your microSD card.

Win32diskimagewriter is capable of writing to almost all sorts of media, so make sure that you aren't telling it to overwrite your USB stick or hard drive. *This is very important!*

Fig.3 shows an example of what the Win32diskimagewriter program looks like just before writing to the card. Finally, click 'Write'. This process may take ten minutes or even longer, depending on the speed of the card and other factors.

Once the write has completed successfully, remove the microSD card from your computer and insert it into the Raspberry Pi.

If you want to set up the software from scratch, refer to the panel overleaf with the step-by-step procedure.

Connecting to a host

To control the Pi and trigger speech synthesis and audio playback, you need a device which can communicate over a serial UART interface. We used an Arduino Leonardo microcontroller board, as it has two serial ports; one is a virtual serial port connected to the USB interface, while the other is a hardware-based serial port which is connected to a pair of accessible I/O pins.

Initially, we'll just use the Leonardo as an interface between your PC and the Raspberry Pi for testing purposes. Later, you can program the Leonardo to trigger speech and sounds by itself.

Start by programming the Leonardo with our **USB-Serial_for_Leonardo** sketch (also available for download from the July 2020 page of the *PE* website).

This makes the Leonardo equivalent to a simple USB/serial converter. It won't work on Uno boards, as they only have one hardware serial port.

If you don't have a Leonardo, any other Arduino board based on the ATmega32U4 microcontroller should work. For example, you could use a small 'Beetle' board, like the one we used for the *PC Remote Control Interface* in the August 2019 issue.

Connect the Leonardo as shown in Fig.4. This allows it to supply 5V to the Raspberry Pi board. While there will inevitably be a voltage drop across the jumper wires supplying current to the Pi, we did not find this to cause any problems.

If you do find you have power problems on the Pi, or noise in the audio, you may be able to solve this by powering the Pi directly using its own micro USB socket and an external USB plugpack.

In this case, don't connect the 5V supply wire. The Arduino board can still get its power from the computer.

Another option for the test procedure is to use a CP2102 USB/serial converter. To do that, simply wire up the converter to CON2 on the hat, but note that you will need to leave out or remove the 1kΩ resistor at upper right as these devices operate with 3.3V signalling levels.

Terminal software

While it's possible to use the Arduino serial monitor to communicate with the Pi via the Arduino, other terminal programs such as PuTTY or TeraTerm have better terminal emulation support which suits the Raspberry Pi interface.

In particular, if you wish to do any file editing on the Pi (which may be necessary to enable specific settings), a proper terminal program is mandatory.

Regardless of which terminal software you use, you will need to connect to the Pi at 115,200 baud with eight bits and no parity (8-N-1).

Generating speech

If you have chosen the step-by-step setup, you will have already tested out the *Speech Synthesiser*. If you have installed the pre-configured card image, then you will want to see what the *Speech Synthesiser* is capable of before setting up your controller.

After the Pi has booted, you need to log in using the username 'pi' and password 'raspberry'. Later, if you set up an

Step-by-step software set-up procedure

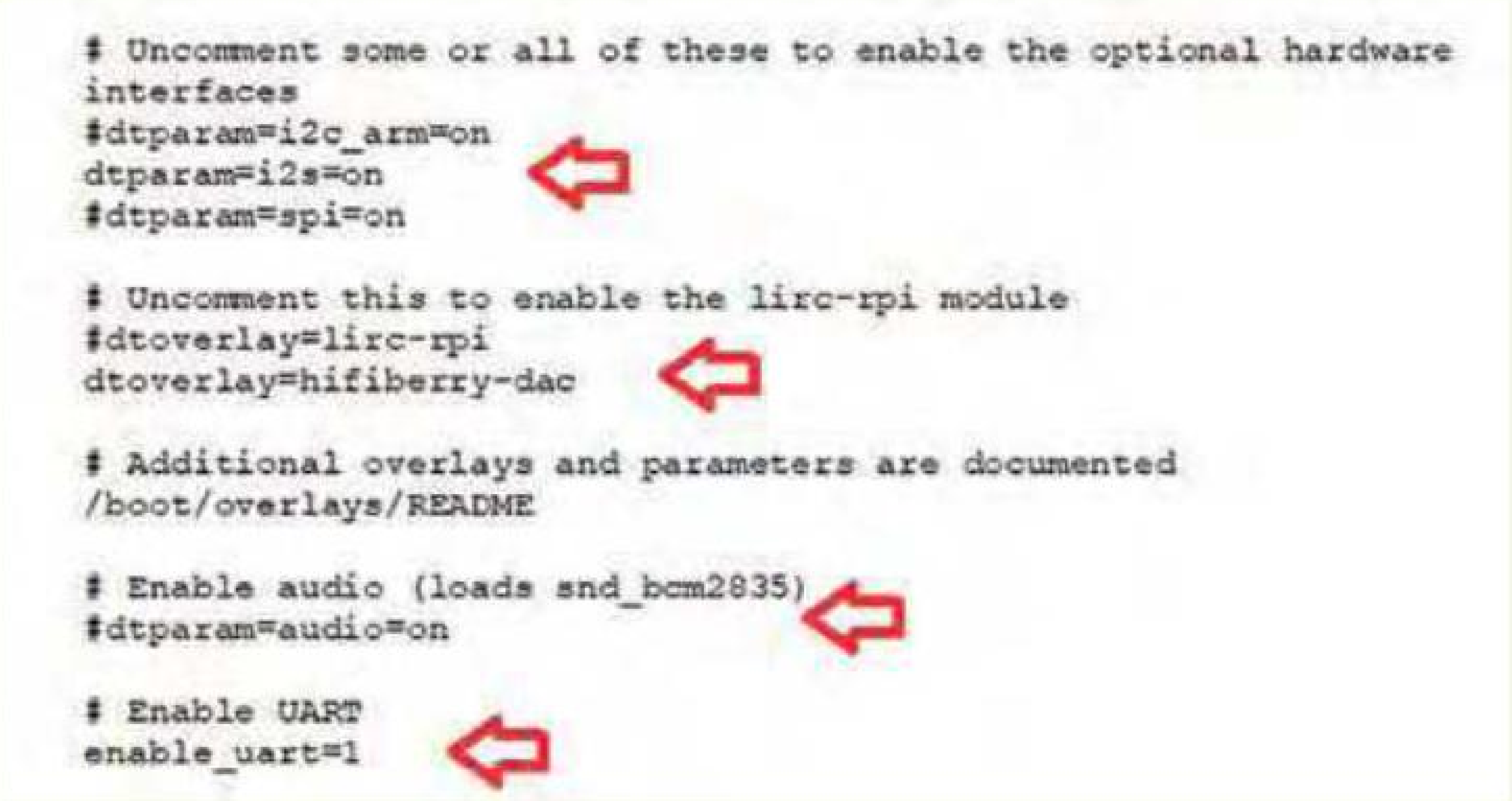
This process is more involved than simply using the image file, as described in the main body of this article, but gives you a lot more options. We don't recommend doing this with a Raspberry Pi variant that lacks Wi-Fi since that is a lot more fiddly. But you could set up the SD card on a Raspberry Pi equipped with Wi-Fi and then plug it into a Pi Zero.

The first step involves writing a Raspbian Lite image to the card, which is practically the same process as we described for our custom image. These files are available for download from: **www.raspberrypi.org/downloads/raspbian/**

We used the November 2018 version of Raspbian Lite. Write the Raspbian Lite image to the card using Win32diskimagewriter, Etcher or dd, as described in the text. Under Windows, there should be two drives created, one named 'boot' and another that Windows cannot recognise. Windows will say that it wants to format the unrecognised partition, but do not let it!

The initial contents of the boot drive are as shown in Fig.6. Open this drive and find the file called 'config.txt', then open it with a text editor such as Wordpad or Notepad++. Some versions of Notepad do not recognise the line endings that Linux uses, and may not display the file correctly, so we do not recommend that you use it.

Now scroll to the end of the file and make the four changes shown in Fig.7.



```
# Uncomment some or all of these to enable the optional hardware
interfaces
#dtparam=i2c_arm=on
dtparam=i2s=on
#dtparam=spi=on

# Uncomment this to enable the lirc-rpi module
#dtoverlay=lirc-rpi
dtoverlay=hifiberry-dac

# Additional overlays and parameters are documented
/boot/overlays/README

# Enable audio (loads snd_bcm2835)
#dtparam=audio=on

# Enable UART
enable_uart=1
```

Fig.7: we've made four changes to the 'config.txt' file on our image, as shown here. These set up the Pi to send audio to our DAC and amplifier board, and to turn on the UART to enable serial communications.

The first and third enable the I²S output, to send data to the DAC on the hat, and disable the default audio output (which is via the HDMI display connector). The second configures the I²S output to suit the DAC we are using. The fourth change allows the console to be accessed over the UART serial port.

If you want to make any more changes to this file, now is the time, as it will be easier to perform edits on a PC than on the Pi. Save the file when finished.

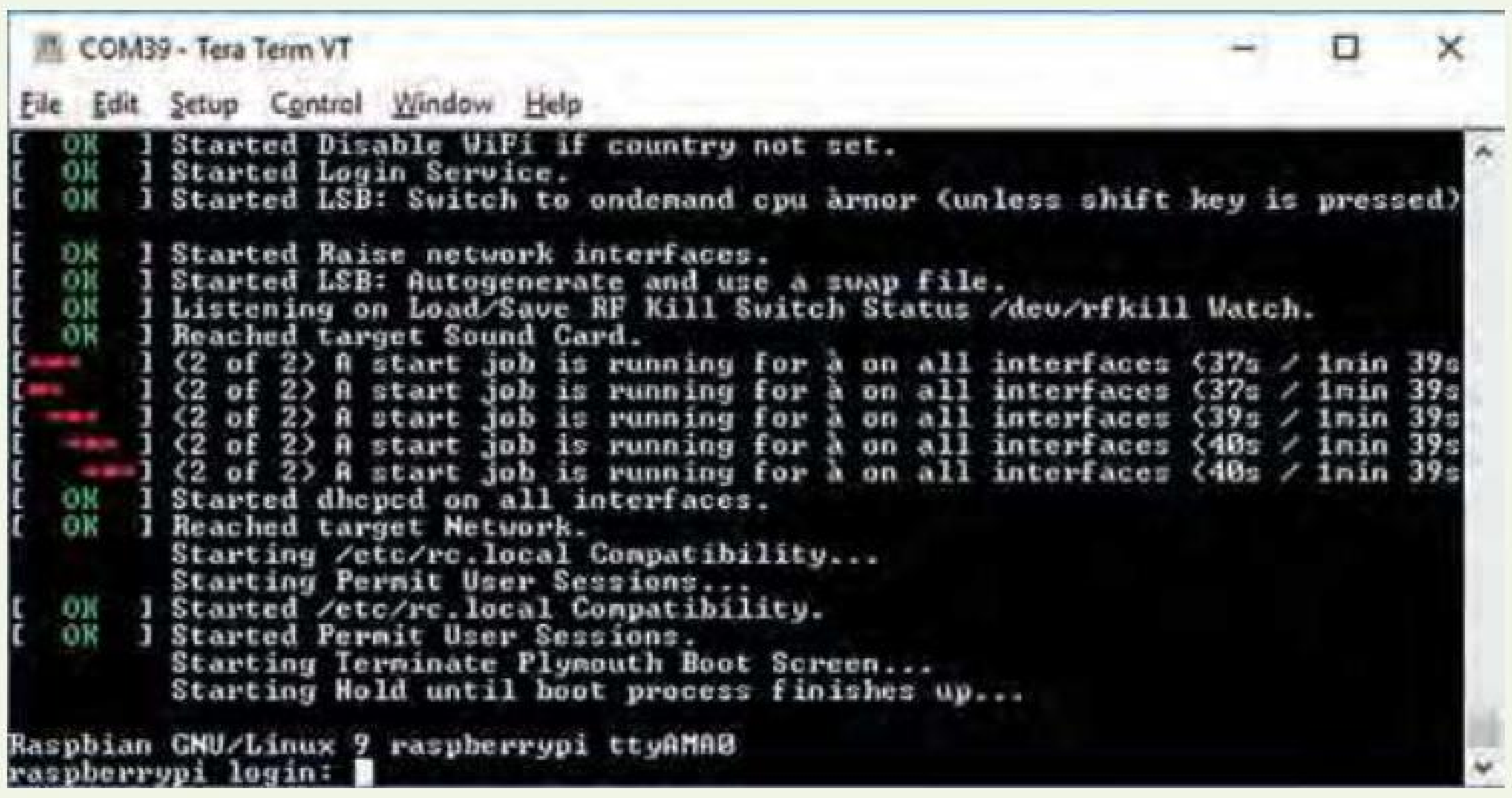
Now you need to create a text file on the boot drive named 'wpa_supplicant.conf', and edit it to contain the following lines:

```
country=AU
ctrl_interface=DIR=/var/run/wpa_supplicant GROUP=netdev
update_config=1
network={
ssid="network"
psk="password"
key_mgmt=WPA-PS
}
```

Change the 'country', 'ssid' and 'psk' values to match those of your own Wi-Fi network, and then save the file.

If you think you might want to use SSH to access the Pi, create a file named 'ssh' in the root of the boot drive. The file doesn't need to contain anything; it merely needs to exist. Now safely remove the microSD card from your PC and insert it into the Pi's microSD card slot. Connect it to your host microcontroller, or whatever you are using to communicate with the Pi over its UART serial port.

Power it up and open to the serial port on the Pi at 115,200 baud. After about five seconds, you should see the screen fill with boot messages. When the Pi connects to your Wi-Fi network, a message showing its IP address can be seen; this is handy if you wish to use SSH for further communication.



```
[  OK  ] Started Disable WiFi if country not set.
[  OK  ] Started Login Service.
[  OK  ] Started LSB: Switch to ondemand cpu arnor (unless shift key is pressed)

[  OK  ] Started Raise network interfaces.
[  OK  ] Started LSB: Autogenerate and use a swap file.
[  OK  ] Listening on Load/Save RF Kill Switch Status /dev/rfkill Watch.
[  OK  ] Reached target Sound Card.
[***   ] (2 of 2) A start job is running for a on all interfaces (37s / 1min 39s
[**    ] (2 of 2) A start job is running for a on all interfaces (37s / 1min 39s
[ ***  ] (2 of 2) A start job is running for a on all interfaces (39s / 1min 39s
[  *** ] (2 of 2) A start job is running for a on all interfaces (40s / 1min 39s
[   ***] (2 of 2) A start job is running for a on all interfaces (40s / 1min 39s
[  OK  ] Started dhcpcd on all interfaces.
[  OK  ] Reached target Network.
         Starting /etc/rc.local Compatibility...
         Starting Permit User Sessions...
[  OK  ] Started /etc/rc.local Compatibility.
[  OK  ] Started Permit User Sessions.
         Starting Terminate Plymouth Boot Screen...
         Starting Hold until boot process finishes up...

Raspbian GNU/Linux 9 raspberrypi ttyAMA0
raspberrypi login:
```

Fig.8: if you can see the login prompt in your terminal window, the Pi is booting correctly, and serial communication is working.

After a minute, you will see the login prompt, as shown in Fig.8. The default username is 'pi' and the default password is 'raspberry'. Enter these, and you will end up at the command prompt, from which we can continue to set up the Pi. Run the following command to update the package list, by typing the command and then pressing Enter. It may take a few minutes, or even longer:

```
sudo apt update
```

Then run:

```
sudo apt-get install espeak-ng raspi-gpio madplay
```

This installs the **espeak-ng**, **raspi-gpio** and **madplay** programs. You may be prompted during the install; press 'y' and Enter to proceed. While the raspi-gpio program is not necessary for the Speech Synthesiser, it will be handy if you wish to use the Pi's other GPIO (general purpose input/output) pins. At this point, everything should be working sufficiently to allow the Speech Synthesiser to function. It can be tested by running this command at the prompt:

```
espeak-ng "testing"
```

You should hear the word 'testing' coming through the speakers.

Arduino (or another device) to control the Pi directly, you will need to program it to wait for the login prompt and then send these strings, followed by newline characters, so that it can log in automatically. Our sample software demonstrates how to do this. The espeak-ng program we're using for speech synthesis has a multitude of options, and a full list of command parameters can be listed by typing the command:

```
espeak-ng - - help
```

For example, using the voice parameter, we can apply a different accent. The parameters start with a dash and are usually listed before the text to be spoken. For example, type:

```
espeak-ng -ven-us "testing"
```

You should then hear the word 'testing' in an American accent. Or try:

The next step is to set the microSD card to be read-only. Before you do this though, you may wish to install more programs or copy other files, as it will be easier now than later.

We say we are setting the microSD card to be read-only, note that this is only a software setting this is used by the Pi and does not affect whether or not it can be written by other systems. There also some utilities installed which allow the Pi to use a ramdisk overlay, for any programs that expect to be able to write to the disk.

If you wish to write files to the ramdisk for your own application, the easiest way is to create a file in the /tmp folder, which exists on the ramdisk. But note that its contents will be lost the next time the Pi is rebooted or powered down. To set up the read-only SD card, run the command:

```
wget https://raw.githubusercontent.com/adafruit/
Raspberry-Pi-Installer-Scripts/master/read-only-fs.sh
```

This downloads the required script. When the download completes successfully, run this command:

```
sudo bash read-only-fs.sh
```

This will provide several prompts to be answered before applying its settings.

There are options to set a GPIO pin as a jumper to GND, to allow write access (the jumper is only read at boot time and applies until the next reset). We suggest setting this to GPIO21, as it can easily be jumpered to GND by placing a jumper across two pins of the GPIO header.

This is actually one of the pins used for the I^2S audio data, but the jumper only needs to be placed long enough to be detected at boot time, so will not interfere with the audio. Fig.9 shows the pin allocations for the Raspberry Pi header, including the suggested jumper location.

GPIO16 can be set to allow a jumper or external transistor to shut down the Pi. Both of these pins can be configured differently in the script. Just follow the prompts.

You can also choose to force the Pi to reboot on a kernel panic (ie, an unrecoverable operating system fault), which may be handy, although that is unlikely to happen.

Now that's all done, download and install some packages and apply the settings you have chosen. You can reboot after this by running the command:

```
sudo reboot
```

The software on the Pi has now been set up and is ready to use.

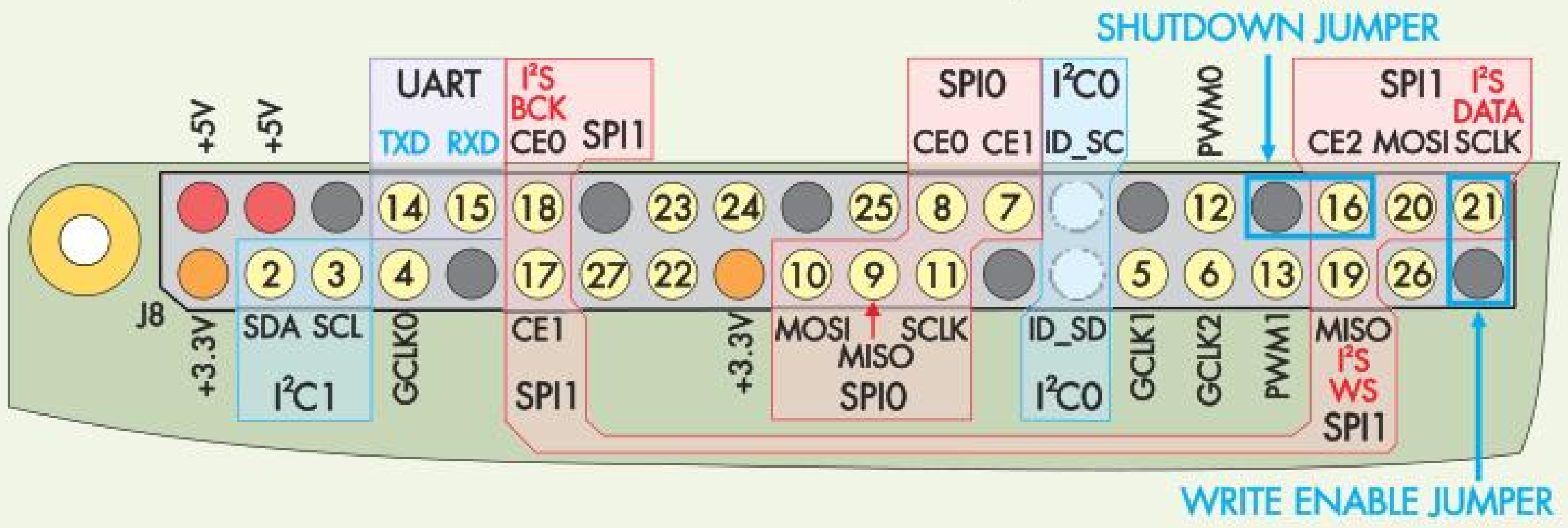


Fig.9: pinout of the Raspberry Pi's 2x20 way header, with the functions used by our software shown in red (I^2S audio data) and blue (serial transmit/receive), along with the recommended shutdown and write-enable jumper locations. If you fit a stackable header to the hat board, jumpers and other accessories can still be easily connected to the Pi.

```
espeak-ng -s 125 -v en+f5 “testing”
```

This will also say 'testing', but in a female-sounding voice. Of course, you can modify the text inside the quotes to make it say different words and phrases.

Other parameters such as reading speed, voice pitch and volume can also be adjusted similarly. See the output of the 'help' command mentioned above.

Parts list (audio hat)

1 double-sided PCB coded 01106191, 65 x 31mm – available from the PE PCB Service
1 2x20 way header socket (CON1) [Jaycar HM3228 or Altronics P5387 for stackable variant]
1 4-way header or socket (CON2) for connection to the host microcontroller
2 2-way male header (CON3, CON4) [optional, for speaker connections]
1 3-way male header (CON5) [optional, line out]

Semiconductors
2 LM386 audio amplifier ICs (IC1,IC2)
1 TDA1543 stereo DAC IC (IC3) (available on eBay – see below)*

Capacitors
2 100µF 10V electrolytic
2 10µF multi-layer ceramic [eg, Digi-key Cat 445-181284-ND]
2 100nF MKT or multi-layer ceramic
2 10nF MKT

Resistors (all 1/4W 1% metal film)
3 1kΩ   2 470Ω

Other parts for complete Speech Synthesiser
1 Raspberry Pi Zero, Zero W or Zero WH [eg, from https://thepihut.com]
1 power supply to suit Raspberry Pi
1 microSD card, 2-32GB
1 or 2 small 8Ω speakers [eg, Jaycar AS3004]
1 microcontroller board (eg, Arduino Leonardo)
4 jumper wires to connect a microcontroller to Speech Synthesiser board
Wire or jumper wires to connect speakers

* Note that the TDA1543A, which is now much more common to find than the TDA1543, is not directly compatible. It expects a different digital audio format. We have revised software, which allows you to use the TDA1543A, available for download.

Playing MP3 files and internet radio

As we noted earlier, you can also use 'madplay' to play MP3 files or internet radio streams. Using this software is straightforward. For example, issue the following command:

```
madplay file.mp3
```

This will play the 'file.mp3' track, assuming it is located in the current directory of the Pi. If the file name has spaces or other special characters in it, put the name in quotes (single or double). You can issue this command:

```
madplay - -help
```

This lists the command line parameters that madplay accepts.

To play an internet radio stream, you will need a version of the Pi with Wi-Fi, and that Wi-Fi needs to be configured to connect to the internet via your router.

For this task, we're combining two Linux commands: the aforementioned madplay, to play the audio, plus a package called 'wget', which downloads the audio stream over the internet.

These are combined in a single command, with the content of the stream being piped by the wget command from its source URL to the input of madplay. The stream will continue unless there is an error, or it can be stopped early by pressing Ctrl-C. For example:

```
wget -O - “http://us5.internet-radio.com:8487/”
  | madplay -
```

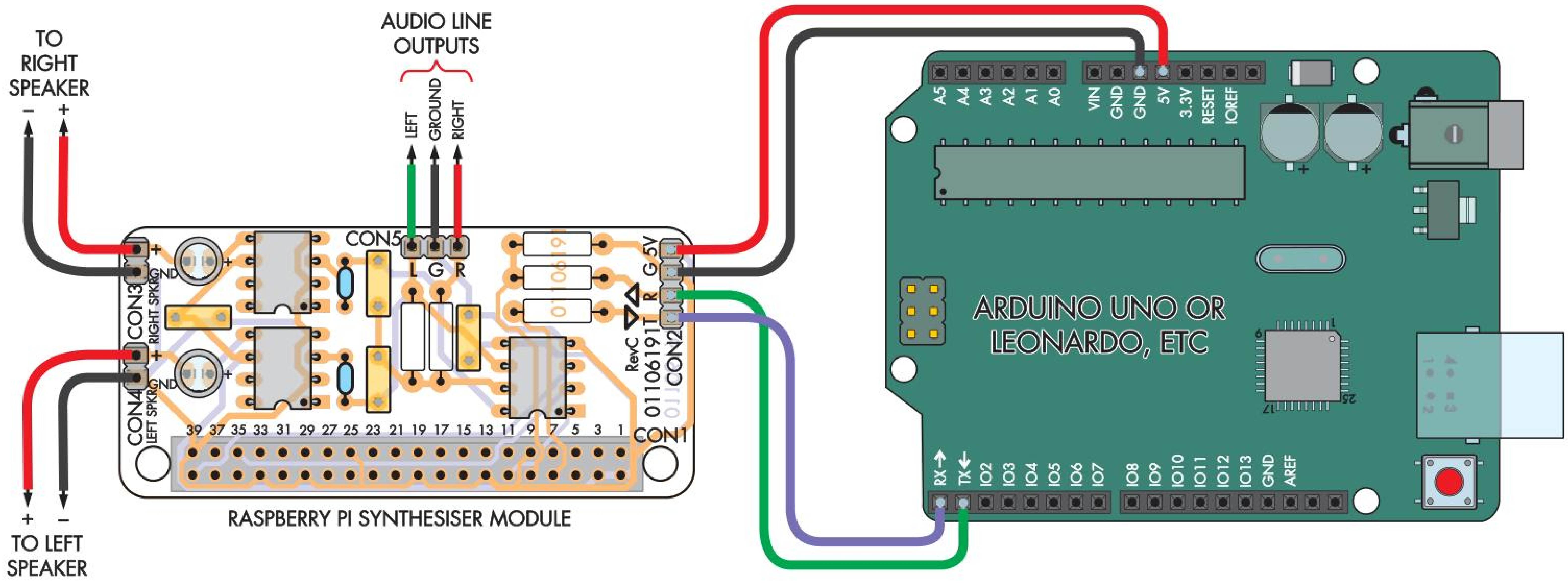

TO RIGHT SPEAKER
– +
AUDIO LINE OUTPUTS
LEFT
GROUND
RIGHT
CON5
L G R
CON3
RIGHT SPKR
GND
CON4
LEFT SPKR
GND
39 37 35 33 31 29 27 25 23 21 19 17 15 13 11 9 7 5 3 1
CON1
RevC
01106191
CON2
G
5V
R
T
+ –
TO LEFT SPEAKER
RASPBERRY PI SYNTHESISER MODULE
A5 A4 A3 A2 A1 A0
VIN GND GND 5V 3.3V RESET IOREF
ARDUINO UNO OR LEONARDO, ETC
RX TX IO2 IO3 IO4 IO5 IO6 IO7 IO8 IO9 IO10 IO11 IO12 IO13 GND AREF

Fig.4: connect the Leonardo board to the *Speech Synthesiser* as shown, for testing or to develop your own Arduino code to drive the *Synthesiser*. Note that the Pi will draw a few hundred milliamps from the 5V supply, so ensure that it can get the power it needs or you may have glitches.

It isn't always obvious what the URL is for the actual radio stream, as you're expected to use an online directory to find and play the streams.

We found it useful to visit **www.internet-radio.com** and then opening up each .m3u file in a text editor (eg, notepad) to determine each station's stream URL.

Putting this URL into the above command should then allow you to play that station using the Pi.

Controlling this all automatically

Our final goal was to be able to use the Arduino board to control the *Speech Synthesiser* and audio playback automatically. To this end, we've created a basic sample sketch which communicates with the Pi, including the login process.

Any text sent to the Arduino over the regular serial monitor is then sent to the Pi as a command, to be spoken.

Note though, if the Pi is still booting when you send the text, you will have to wait for it to finish before hearing it spoken.

The sample sketch is called **Pi_TTS_Interface** and is again available for download from the *PE* website. Upload this to the Leonardo board using the usual procedure and open a serial terminal or the serial monitor.

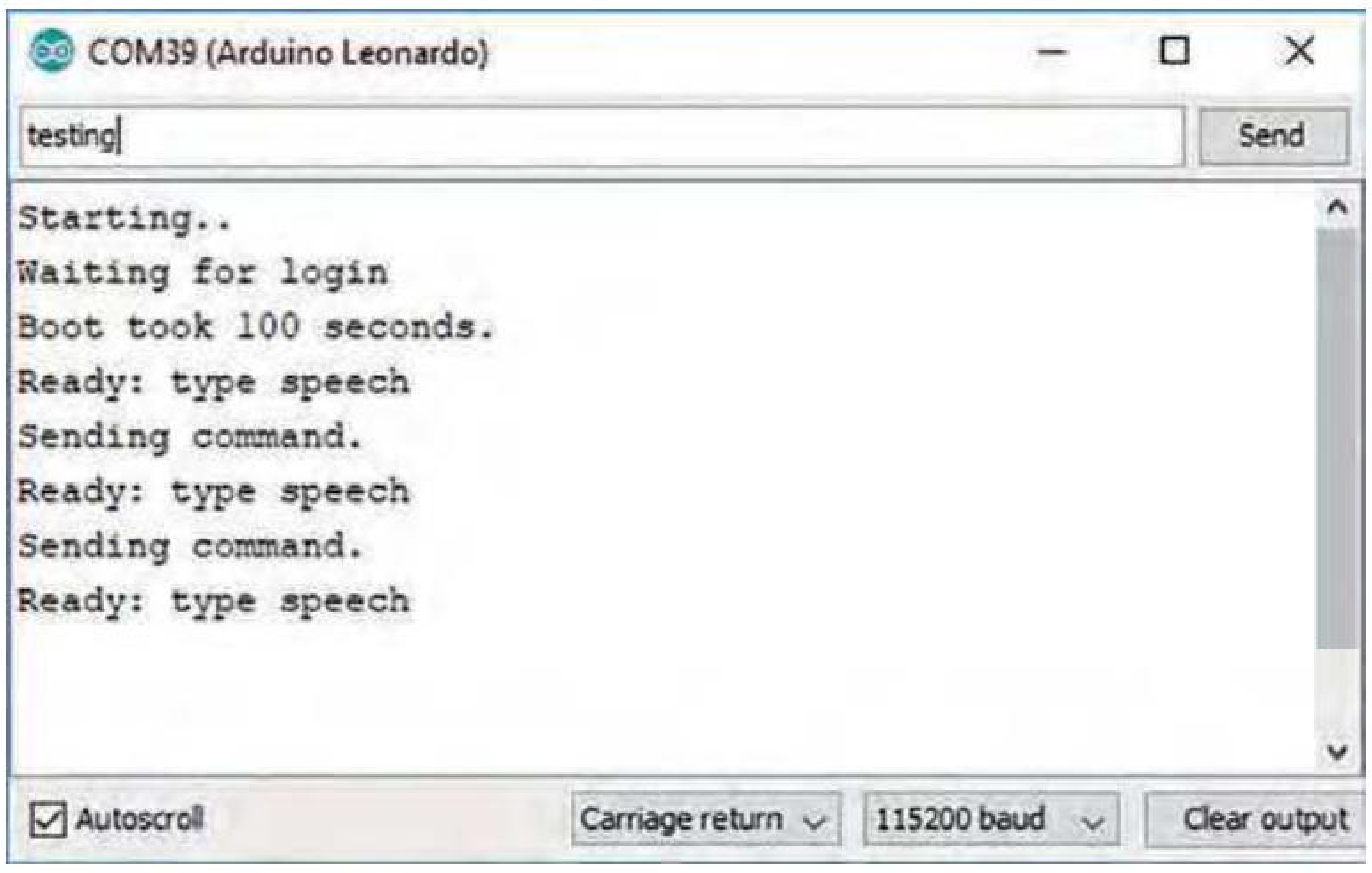
The sketch will report on its status and prompt for text to be spoken when ready. An example of the output of this sketch is shown in Fig.5.

You can use this sketch as a starting point for your own voice control schemes. As the cliche says: the sky's the limit!

What else can you do?

As a small computer in its own right, the Pi is capable of much more than what we've outlined here, especially the versions equipped with Wi-Fi such as the Pi Zero W.

There's a lot of information available on the internet on how to program the Raspberry Pi, so if you're keen to make yours do more, head over to your favourite search engine and start investigating the possibilities. You'll learn a lot more by 'doing' than by 'reading!'

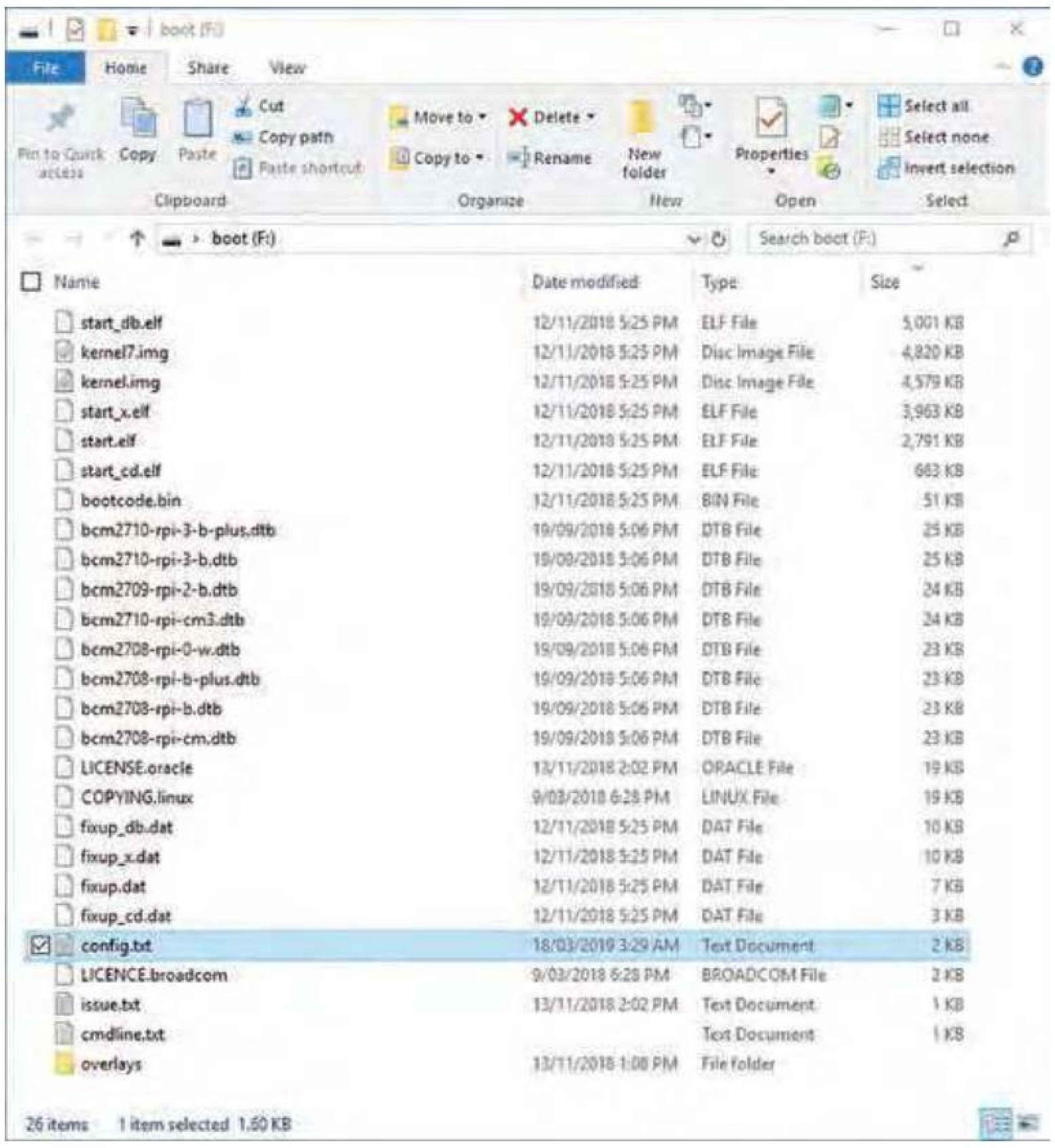

COM39 (Arduino Leonardo)
Send
Autoscroll
Clear output

testing

```
Starting..
Waiting for login
Boot took 100 seconds.
Ready: type speech
Sending command.
Ready: type speech
Sending command.
Ready: type speech
```

☑ Autoscroll   Carriage return   115200 baud

Fig.5 (above): our sample program logins into the Pi's console and then sends commands to speak whatever is typed into the serial monitor. When the 'Ready: type speech' prompt appears, it is ready for speech synthesis.


boot (F:)
File
Home
Share
View
Pin to Quick access
Copy
Paste
Cut
Copy path
Paste shortcut
Clipboard
Move to
Copy to
Delete
Rename
Organize
New folder
New
Properties
Open
Select all
Select none
Invert selection
Select
Search boot (F:)

boot (F:)

Name	Date modified	Type	Size
start_db.elf	12/11/2018 5:25 PM	ELF File	5,001 KB
kernel7.img	12/11/2018 5:25 PM	Disc Image File	4,820 KB
kernel.img	12/11/2018 5:25 PM	Disc Image File	4,579 KB
start_x.elf	12/11/2018 5:25 PM	ELF File	3,963 KB
start.elf	12/11/2018 5:25 PM	ELF File	2,791 KB
start_cd.elf	12/11/2018 5:25 PM	ELF File	683 KB
bootcode.bin	12/11/2018 5:25 PM	BIN File	51 KB
bcm2710-rpi-3-b-plus.dtb	19/09/2018 5:06 PM	DTB File	25 KB
bcm2710-rpi-3-b.dtb	19/09/2018 5:06 PM	DTB File	25 KB
bcm2709-rpi-2-b.dtb	19/09/2018 5:06 PM	DTB File	24 KB
bcm2710-rpi-cm3.dtb	19/09/2018 5:06 PM	DTB File	24 KB
bcm2708-rpi-0-w.dtb	19/09/2018 5:06 PM	DTB File	23 KB
bcm2708-rpi-b-plus.dtb	19/09/2018 5:06 PM	DTB File	23 KB
bcm2708-rpi-b.dtb	19/09/2018 5:06 PM	DTB File	23 KB
bcm2708-rpi-cm.dtb	19/09/2018 5:06 PM	DTB File	23 KB
LICENSE.oracle	13/11/2018 2:02 PM	ORACLE File	19 KB
COPYING.linux	9/03/2018 6:28 PM	LINUX File	19 KB
fixup_db.dat	12/11/2018 5:25 PM	DAT File	10 KB
fixup_x.dat	12/11/2018 5:25 PM	DAT File	10 KB
fixup.dat	12/11/2018 5:25 PM	DAT File	7 KB
fixup_cd.dat	12/11/2018 5:25 PM	DAT File	3 KB
☑ config.txt	18/03/2019 3:29 AM	Text Document	2 KB
LICENCE.broadcom	9/03/2018 6:28 PM	BROADCOM File	2 KB
issue.txt	13/11/2018 2:02 PM	Text Document	1 KB
cmdline.txt		Text Document	1 KB
overlays	13/11/2018 1:08 PM	File folder	

26 items   1 item selected 1.60 KB

Fig.6 (right): some files on the microSD card for the Pi can be edited on a PC as the 'boot' volume uses the common FAT file system. This is much easier to do than using the Pi's inbuilt text editor. The config.txt file contains many settings, including which services are started at boot time.

Win a Microchip PIC-BLE Development Board

Practical Electronics is offering its readers the chance to win a Microchip PIC-BLE Development Board (DT100112) – and even if you don't win, receive a 20%-off voucher, plus free shipping for one of these boards.

The PIC-BLE development board makes wireless applications development quick and easy. It combines an eXtreme Low Power (XLP) PIC16LF18456 microcontroller, an ATECC608A CryptoAuthentication secure element and the RN4870 Bluetooth Low Energy Module.

With the board USB interface it not only provides a convenient serial port (virtual UART) and the simplicity of drag and drop programming, but also full programmer and debugger capabilities supported by an award-winning integrated development environment (IDE) the Microchip MPLAB X IDE.

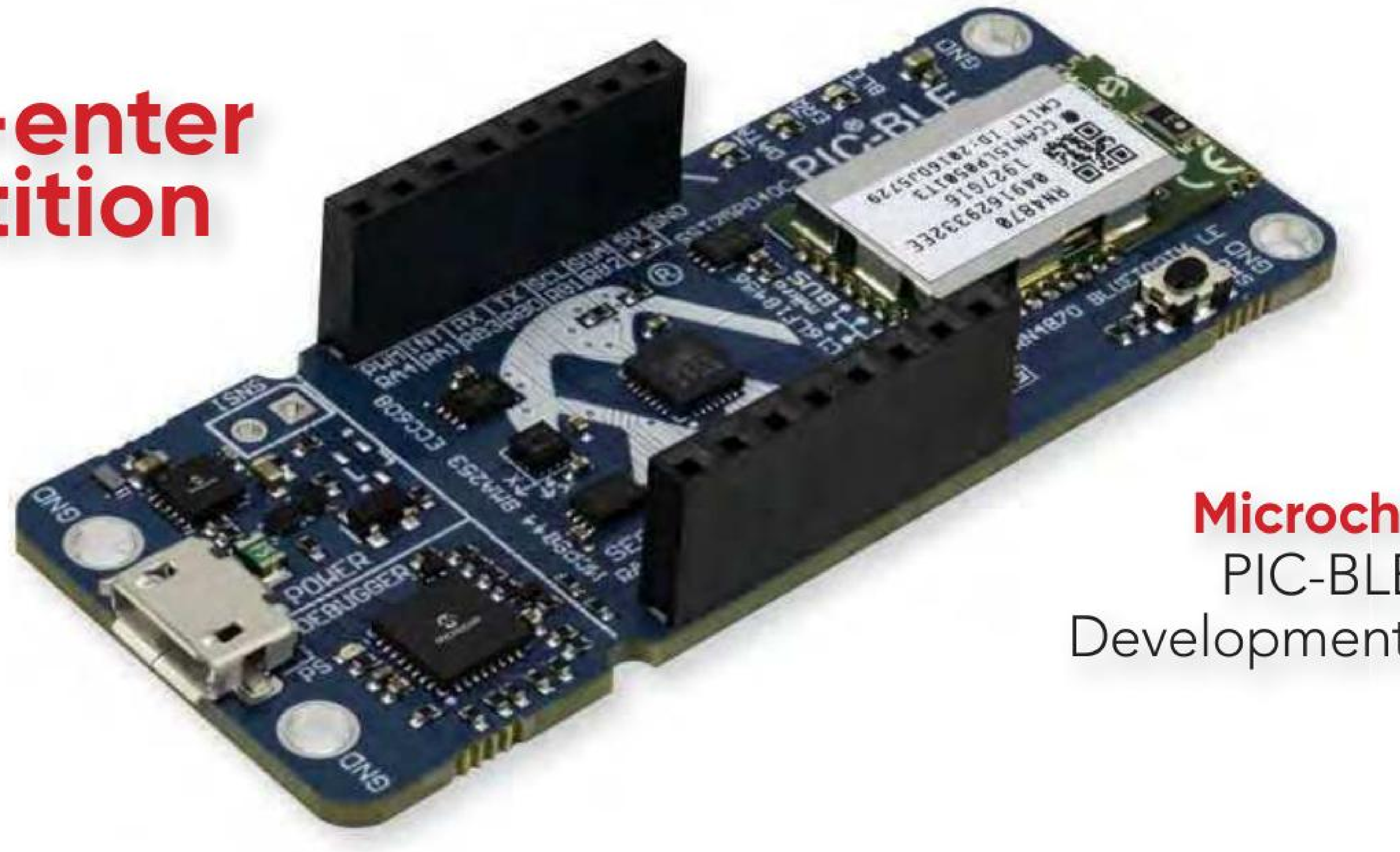
Worth $29.00 (approx £23.50) each

Connect it to your Bluetooth LE capable mobile phone or tablet using the LightBlue app to activate the exclusive graphical user interface and interact with all the board sensors.

The PIC-BLE Development Board is designed to demonstrate that typical BLE applications can be simplified and feature the following elements:

- ■ Smart, Secure and Connected – represented by the PIC16LF18456 microcontroller, ATECC608A secure element and RN4870 BLE module.
- ■ The on-board debugger (PKoB nano) supplies full programming and debugging support through Microchip. MPLAB X IDE. It also provides access to a serial port interface (serial-to-USB bridge) and one logic analyser channel (debug GPIO).
- ■ A mikroBUS socket enables the designer to expand the board's capabilities with selection from 450+ sensor and actuator options.

Free-to-enter competition



Microchip
PIC-BLE
Development Board

How to enter

For your chance to win a Microchip PIC-BLE Development Board or receive a 20% off voucher, including free shipping, enter your details in the online entry form at:

https://page.microchip.com/PE-PIC-BLE.html

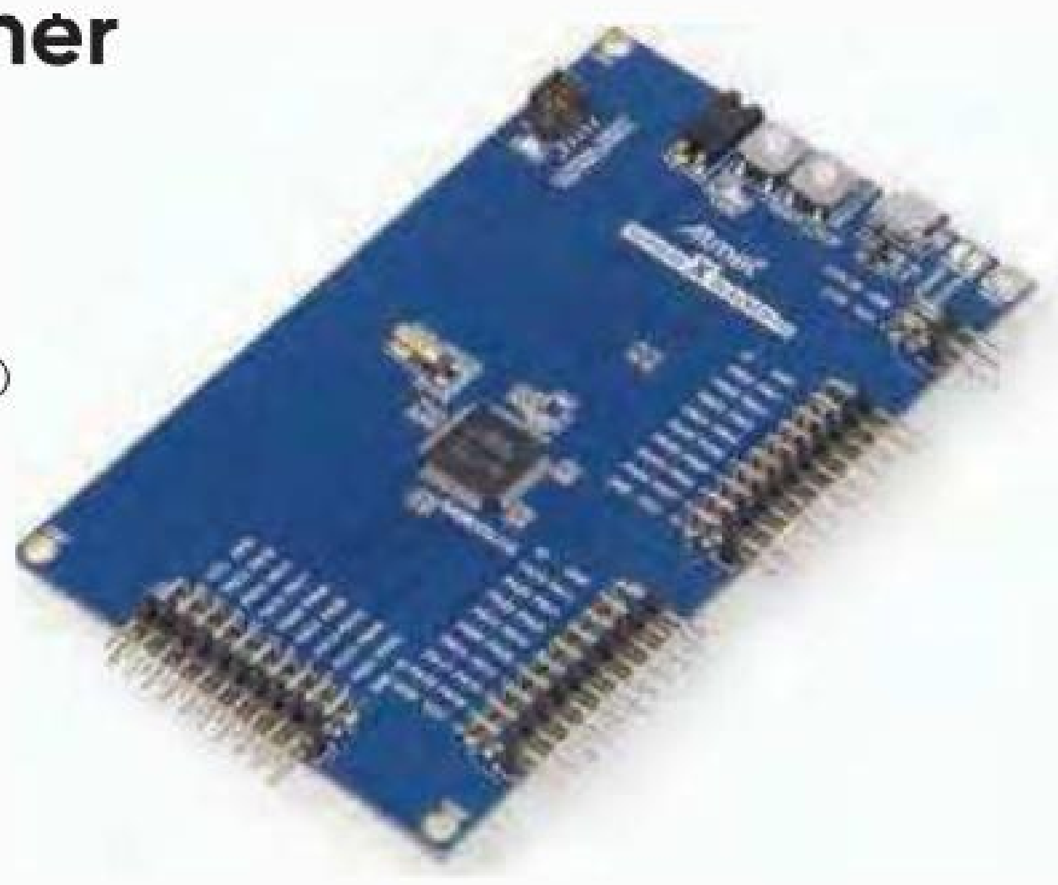
Closing date

The closing date for this offer is 30 June 2020.

March 2020 winner

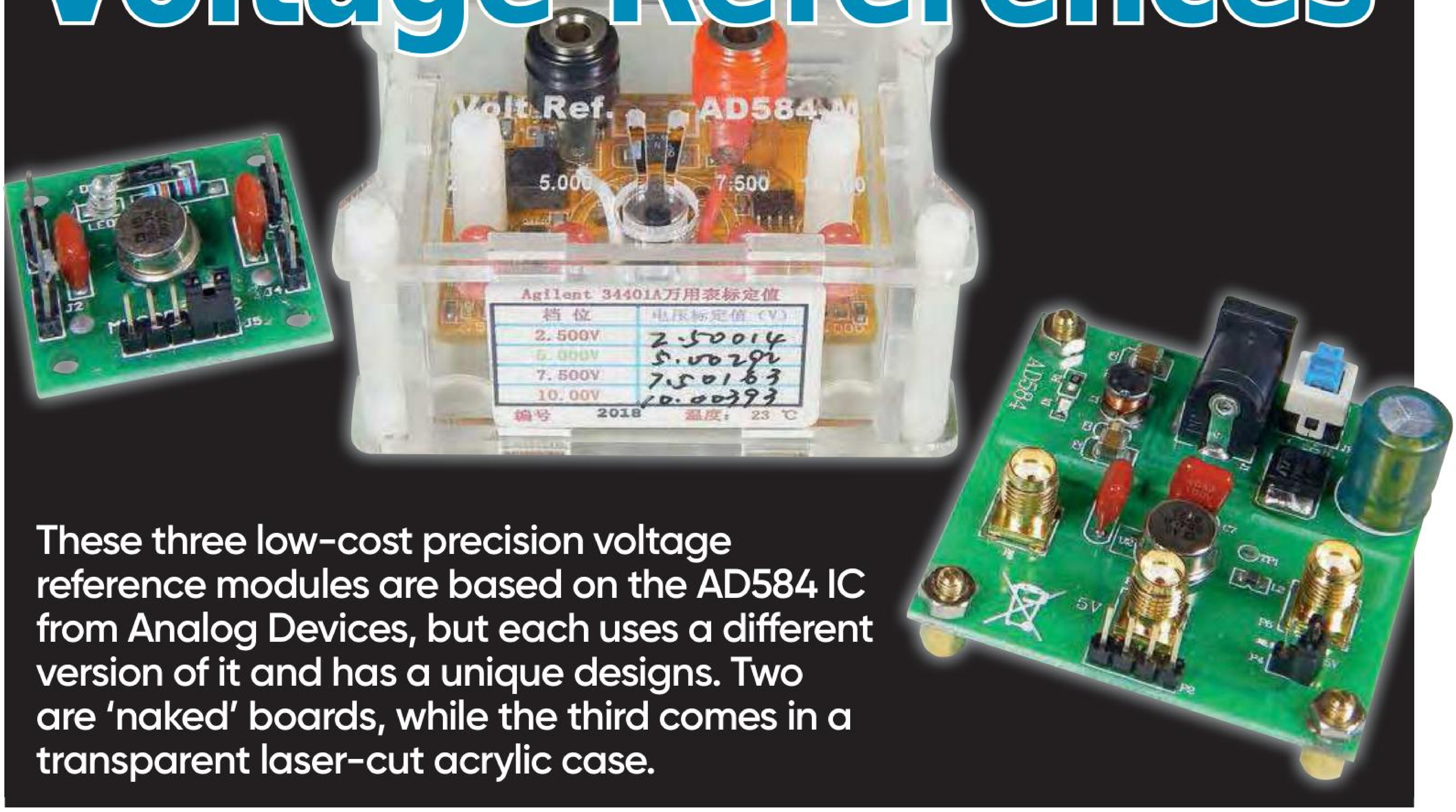
Mark Jones

He won a Microchip SAM D20 Xplained Pro Evaluation Kit



Using Cheap Asian Electronic Modules by Jim Rowe

AD584 Precision Voltage References



These three low-cost precision voltage reference modules are based on the AD584 IC from Analog Devices, but each uses a different version of it and has a unique designs. Two are 'naked' boards, while the third comes in a transparent laser-cut acrylic case.

The ML005-V1.2 is the smallest module, with a PCB measuring 32 × 32mm. You can purchase it from AliExpress for around £4.50 (including delivery): **www.aliexpress.com/item//32853943748.html**

The slightly bigger module has no ID, but its PCB measures 50 × 50mm and it is available from Banggood for around £13.25 (including delivery): **https://bit.ly/pe-jul2020-ad584**

The largest module, from KKMOON, comes in an acrylic case, measuring 70 × 52 × 35mm overall. It is available from suppliers like Banggood and eBay for around £13.00 (including delivery): **https://bit.ly/pe-jul20-kkm**

Each of the modules are based on different versions of the AD584 precision voltage reference device made by Analog Devices (the datasheet can be found at: **https://bit.ly/pe-jul20-ad584-data**). Let's start by looking at how this chip works.

The AD584 device

Analog Devices describe the AD584 as a 'Pin Programmable Precision Voltage Reference'. It comes in a number of versions, all of which are available in an 8-lead hermetically sealed TO-99 metal package. The two lowest-precision versions are also available in an 8-lead plastic DIP. The metal-package versions have an 'H' suffix, while those in the plastic package carry the 'NZ' suffix.

All versions are made using laser wafer trimming (LWT) to adjust the output voltages and also their temperature coefficients. Originally, five versions were available: the AD584J, AD584K and AD584L, all specified for operation from 0-70°C; and the AD584S and AD584T, which are specified for operation between –55°C and +125°C.

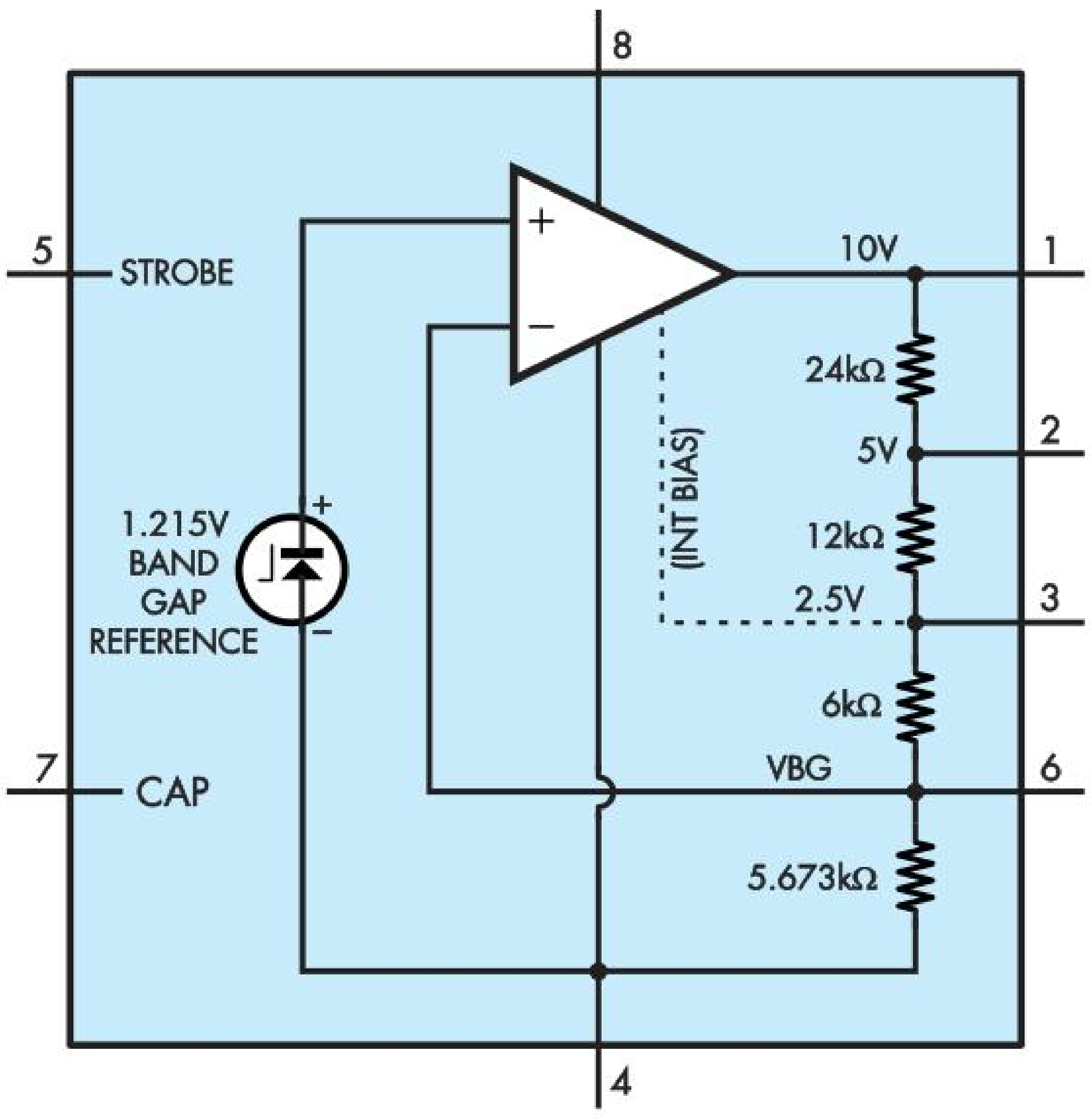
However, the AD584LH version was discontinued by Analog Devices in 2012, so presumably, those used in modules like the one described here are either 'new old stock' (NOS) or have been 'recycled' from used equipment.

The basic specifications of the AD584JH, AD584KH and AD584LH are summarised in Table 1; which can be found at the end of the article. The AD584JH version is the least accurate, while the AD584LH is the most accurate. But note that all three versions have identical specifications when it comes to noise output and long-term stability.

A simplified version of the AD584's internal block diagram is shown in Fig.1. At the heart of the device is a high stability band-gap reference diode providing a 1.215V reference. This is followed by an op amp used as a buffer amplifier, with its voltage gain set by the string of divider resistors connected between its output (pin 1) and common (pin 4) terminals.

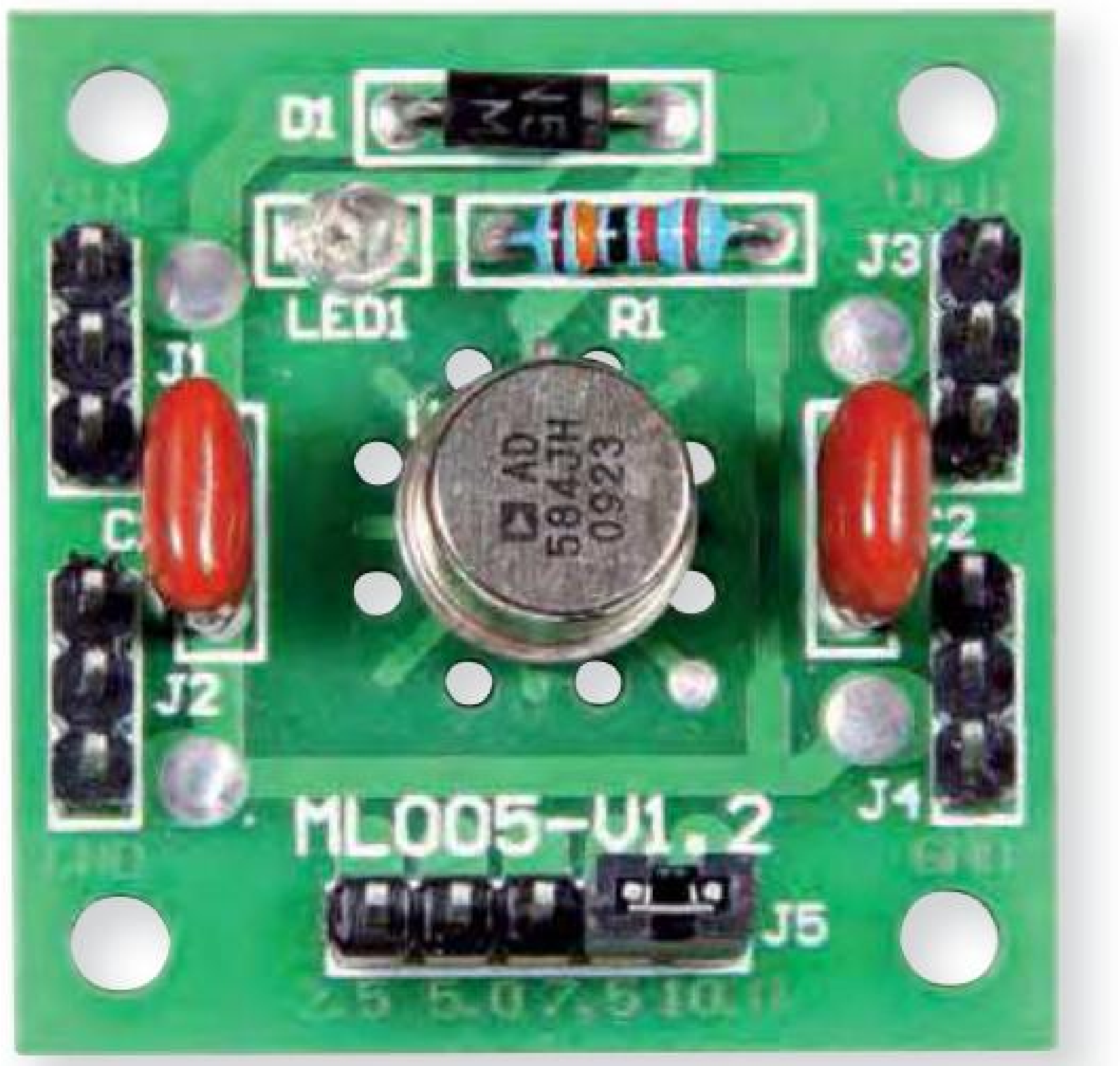
Internal feedback from the lowest tap of the divider string (pin 6, V_{BG}) ensures that the buffer amp maintains V_{BG} at very close to 1.215V, the bandgap voltage. So if a DC voltage between +12-15V is applied to the device between pins 8 and 4, and no external connections are made to pins 2, 3 or 6, it will provide a nominal output voltage of very close to 10V at pin 1.

But if pins 1 and 2 are joined externally, the voltage at pin 1 will drop to



Inside the AD584 chip

Fig.1 (left): the AD584 voltage reference IC used in all these modules contains a very accurate and stable 1.215V laser-trimmed bandgap reference, plus a precision op amp and resistors to amplify that reference to provide four possible output voltages (2.5V, 5V, 7.5V and 10V) depending on which combination of pins 1, 2 and 3 are tied together.



Right: the ML005-V1.2 module shown at nearly twice actual size. Note that searching for 'ML005' online will not find this module, so you will need to search for AD584.

very close to 5V, and if pins 1 and 3 are joined, it will be very close to 2.5V. If pins 2 and 3 are joined, it will settle very close to 7.5V.

Notice also that pins 1, 2 and 3 can be used to source 10V, 5V or 2.5V independently, although pins 2 and 3 cannot provide significant current without affecting accuracy, and so if used, the voltages should be fed through unity-gain buffers. More on that later.

Note that you can't get a buffered 1.25V output from pin 1 by tying pins 1 and 6 together, turning the op amp into a unity gain buffer. This is because the 2.5V tap is used for internal biasing.

There are two pins we have not yet explained in Fig.1: pin 7 (CAP); and pin 5 (STROBE). Pin 7 is provided so you can connect a small capacitor (usually 10nF) between this pin and pin 6 (V_{BG}), to lower the bandwidth of the internal op amp and reduce the output noise level.

Pin 5 is provided to allow the AD584 to be switched on or off by a logic signal. If no current is drawn from pin 5, the device operates normally, but if the pin is pulled down to common/ground, it effectively switches off.

Now let's look at how it's used in the lowest cost module of our three.

The ML005 module

Fig.2 shows the full circuit of the ML005 module, plus the basic map of its PCB. As you can see, this module is essentially a 'bare minimum' design. It contains little more than the AD584 chip plus a few support components and some SIL headers used for input and output connectors, and for programming the desired output voltage.

It uses the 'JH' version of the AD584 chip, so we shouldn't expect too much from it in terms of output precision or temperature stability.

Diode D1 is presumably to protect the AD584 from damage from reversed supply polarity, while LED1 and its rather high-value series resistor is to provide power-on indication.

The 10nF capacitor connected between pins 7 and 6 of the device reduces the output noise level, while SIL header J5 allows setting the module's output voltage by fitting a jumper shunt to one of the four possible positions.

The current drain of the module when operating is less than 1mA, but this will rise if current is drawn from any of the outputs.

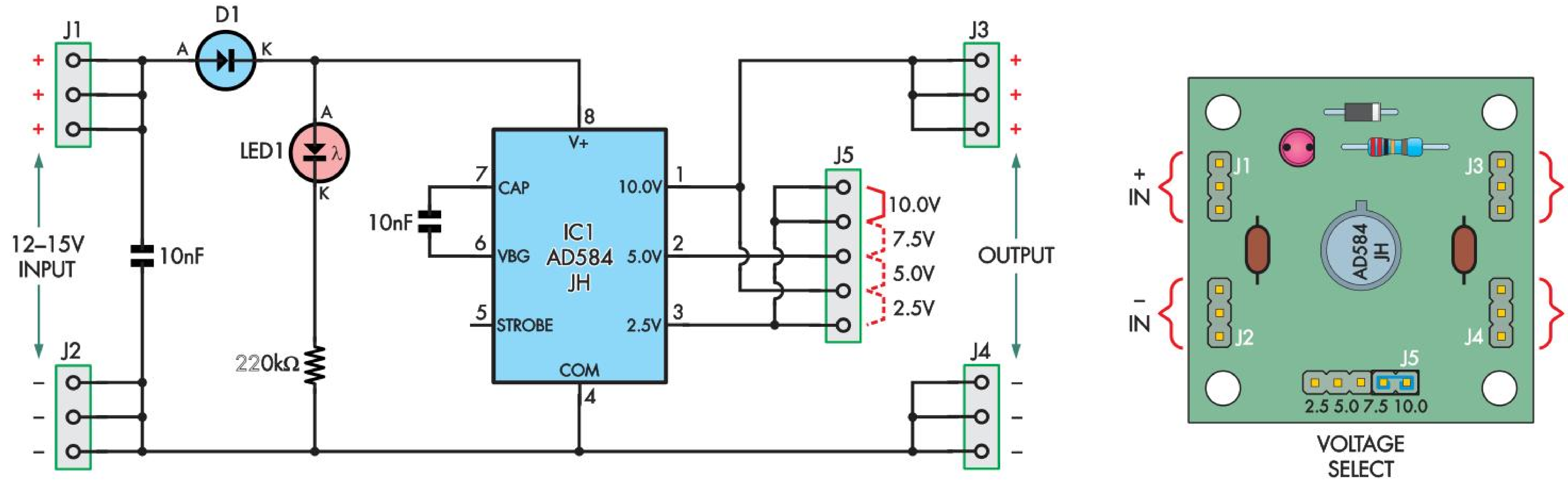
Before we move on to look at the next module, you might like to know how easy it is to give the ML005 module three fixed and buffered outputs of 10V, 5V and 2.5V.

Fig.3 shows all you need to do this: a low-cost dual op amp like the LM358 or the TL072, wired as shown to provide two unity-gain buffers. One is for the 5V output of the module, and the other for the 2.5V output. The 10V output is already buffered by the op amp inside the AD584, so it doesn't need any further buffering.

Note though that this buffer op amp's 'input offset voltage' error term will slightly reduce the accuracy of the output voltages, although typically this figure is no more than a few millivolts.

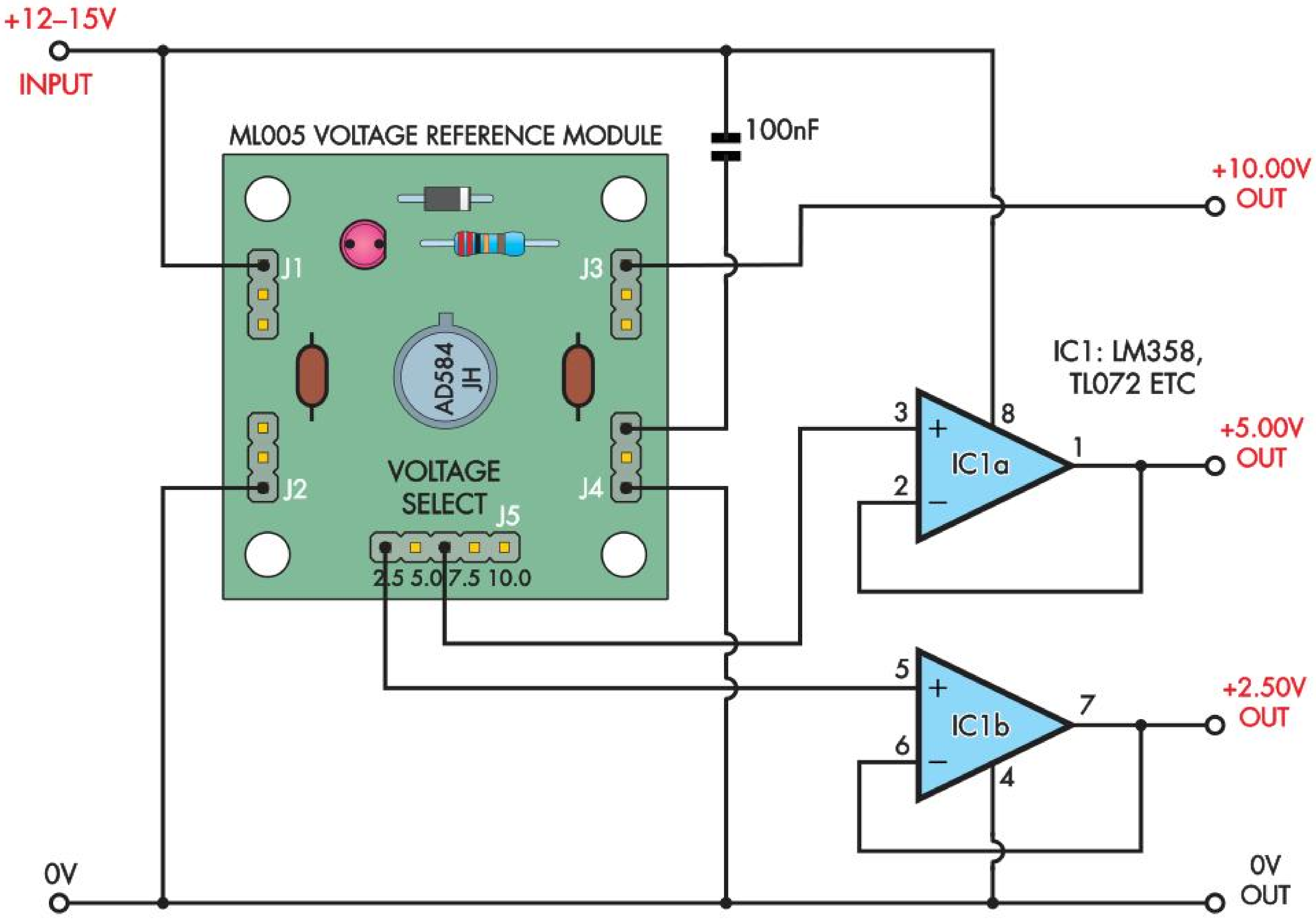
However, it can change with temperature and time. So if you need maximum accuracy, use a precision or chopper stabilised op amp, which will have offset voltages in the microvolt range.

So is it possible to trim the outputs of the ML005 module, to set the output voltages closer to nominal? Yes, it is, using the trimming circuit shown in Fig.4. As you can see it's fairly straightforward; just a 10kΩ multi-turn trimpot connected across the output from



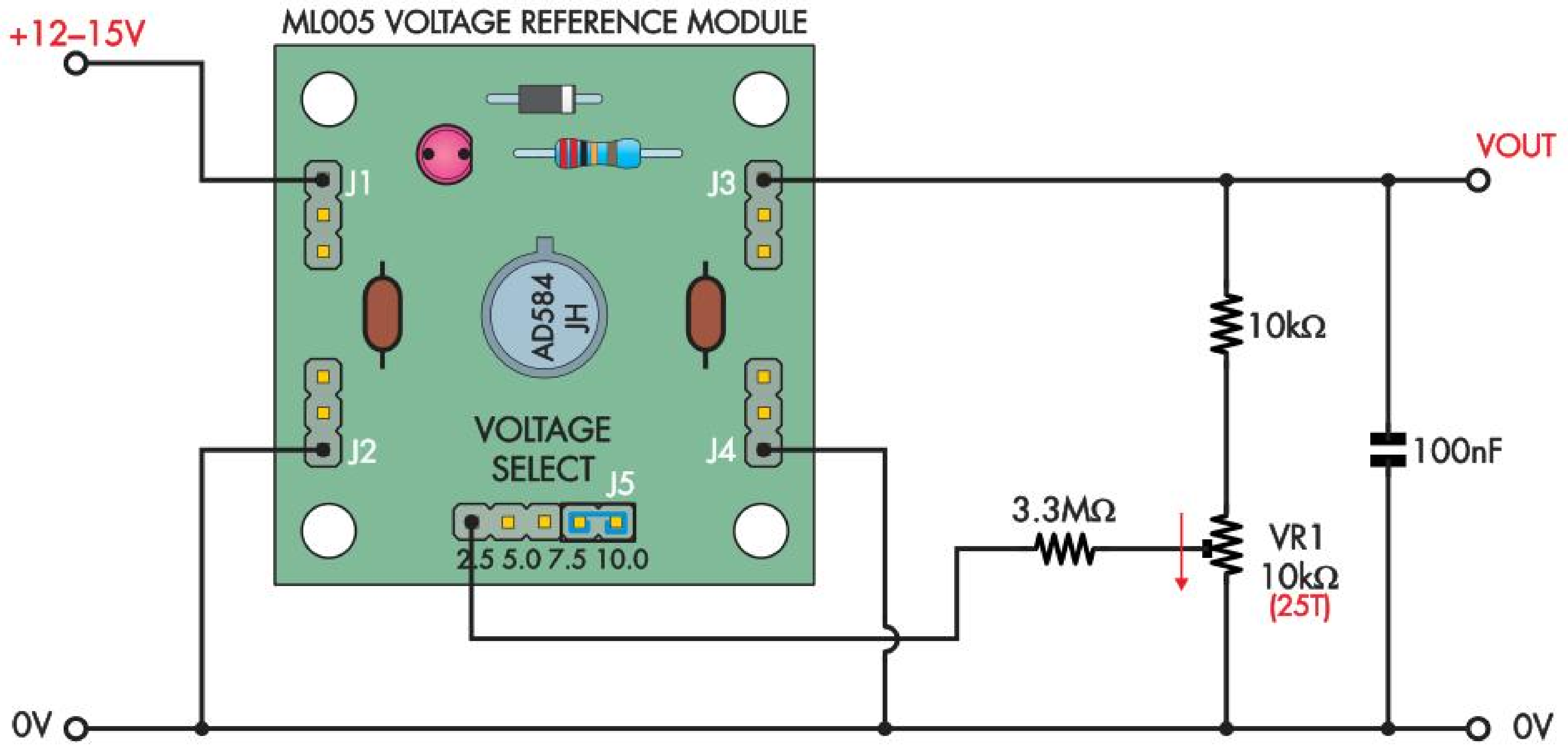
ML005 Precision Voltage Reference module

Fig.2: the circuit and general layout of the basic ML005 reference board. It's a minimalist implementation of an AD584-based voltage reference, with pin header J5 provided to select the output voltage using a jumper shunt.



Giving the ML005 module three fixed, buffered outputs

Fig.3: this circuit shows how to get multiple different reference voltages from the ML005 module simultaneously. While you could use a low-cost dual op amp as suggested here, the voltages would be more accurate and stable if a precision or chopper-stabilised op amp was used.



Trimming the ML005 10V/7.5V/5V output levels

Fig.4: it's quite easy to connect a trimpot to the ML005 module, so that you can adjust its output voltages to be close to the nominal values. You need a very accurate voltmeter to do this. This will work with the output voltage set to one of the 10V, 7.5V or 5V options.

J3 (V_{OUT}) to J4 (0V), with a 10kΩ resistor in series and with its wiper connected to the 2.5V pin of J5 via a 3.3MΩ series resistor.

This allows the outputs to be adjusted over the range of about ±20mV; more than enough to achieve calibration.

The trimpot should be a 25-turn cermet unit, to allow fine adjustment and also provide a low temperature coefficient. The two fixed resistors should also be metal film types. The 3.3MΩ series resistor can be reduced in value for a wider adjustment range, but its value should not be lower than 300kΩ as this would adversely affect the module's stability.

The KKmoon module

Now we turn our attention to the module with all the 'bells and whistles'; the KKMOON (**www.kkmoon.com/p-e0555.html**). It comes housed in a laser-cut transparent acrylic case. The case can be easily disassembled for servicing, if needed.

The designers of this module seem to have gone out of their way to add every feature they could think of.

For a start, they've built in a 3.7V/500mAh lithium-polymer (LiPo) battery, so the unit can be used away from mains power.

Of course, the battery will need to be charged when you are back in your workshop, so they've built in a charger as well, with a 5V input (microUSB socket).

Since the battery only provides about 4.2V even when fully charged, they've also included a DC/DC boost converter to step up the battery voltage to around 13.5V for the AD584.

They've also added circuitry so that the various voltage ranges of the AD584 can be selected in sequence using a single pushbutton switch and LEDs to indicate which output voltage is currently selected.

The circuit (Fig.5) shows the parts they have added to provide all these extra features. The heart of the unit is still the AD584 (IC1). The 'KH' version of the AD584 is being used in this module – the one with performance specifications about twice as tight as those of the 'JH' version.

All of the circuitry at the top and far left in Fig.5 is associated with the unit's battery power operation. The Li-ion cell is charged via IC2 at upper left, using power from a 5V USB source fed in via CON1. IC2 is a Linear Technology LTC4054 charge controller, with pin 3 connected to the positive pole of the cell.

The resistor connected from pin 5 of IC2 (PROG) to ground sets the charging current level, while pin 1 of the device ($\overline{\text{CHRG}}$) goes low when charging is taking place. It's used to indicate when the battery is being charged, via LED1.

The circuitry at centre and lower left is intended to protect the Li-ion battery from damage from overcharging or over-discharge. IC4 is a DW01-P 'Li-ion protector' chip which monitors the battery voltage via its V_{CC} pin (pin 5) and controls battery charging and discharging via pins 3 (CGO) and 1 (DGO), connected to the gates of Q8, an FS8205A dual N-channel power MOSFET.

However, oddly, in the modules we've seen, the sources and drains of Q8 are shorted together by solder blobs, disabling the protection circuitry by permanently connecting the negative side of the battery directly to ground. Perhaps this has been done because the LTC4054 has its own protection circuitry, which may well be sufficient for this application.

IC3 and its associated circuitry at upper right is the boost converter, which steps up the Li-ion battery voltage to around 13.5V, to run IC1. It's a standard configuration using the MC34063A switchmode converter chip. MOSFET Q1 is used as an on/off switch for the boost converter, and hence for IC1 as well.

It's controlled in turn by IC5, shown at lower centre, which is an unmarked microcontroller unit (MCU) in an 8-pin SOIC package. The MCU is also used to perform the output voltage switching of IC1, as well as the indication of the selected output voltage. This is all in response to presses of switch S1, connected between the 'SW' pin of IC5 and ground.

Different outputs of IC5 are used to select the various output voltages available from IC1 by switching on one of the transistors Q5, Q6 or Q7, which then in turn switches on one of the P-channel MOSFETs Q4, Q2 or Q3. These latter devices perform the same purpose as the jumper shunt links on the ML005 module (see Fig.2).

The LEDs indicating which voltage is selected are powered by the base drive currents for Q5, Q6 or Q7.

Because none of the links need to be fitted for IC1 to deliver its 10V output (ie, all those transistors are switched off in this case), the MCU simply activates LED5 via its '10V' output (pin 3) when that output voltage is selected.

So the KKMOON module is much more complex than the ML005 we looked at first, which probably explains why it costs about three times as much. But it does offer a number of extra features, like portable operation and control using a single button. It also uses the superior AD584KH.

Mind you, using a high-frequency step-up converter to provide the 13.5V supply for IC1 might increase the noise level, while using MOSFETs Q2-Q4 to select the lower output voltages might also turn out to have unexpected consequences. We'll look at these aspects a little later.

The unnamed module

The third module is the one on a 50 × 50mm PCB, which carries no ID as such, but is marketed as a 'high precision' module. This is perhaps because it features SMA coaxial connectors for the three main outputs, and is also claimed to use the AD584LH chip, which has the tightest specs of all versions.

The only aspect of the AD584LH which raises one's eyebrows is that, as mentioned earlier, it was discontinued by Analog Devices in 2012, suggesting that the makers of this module either bought a large quantity before then and are still using them up, or that they have salvaged some from used equipment. That's assuming they are genuine AD584LH devices, of course.

The circuit for this module is shown in Fig.6. It's much less complex than the KKMOON module, and only a little more complex than the ML005.

It's designed to run from 15-24V DC, fed in via J1, a standard concentric power jack. S1 is the on/off

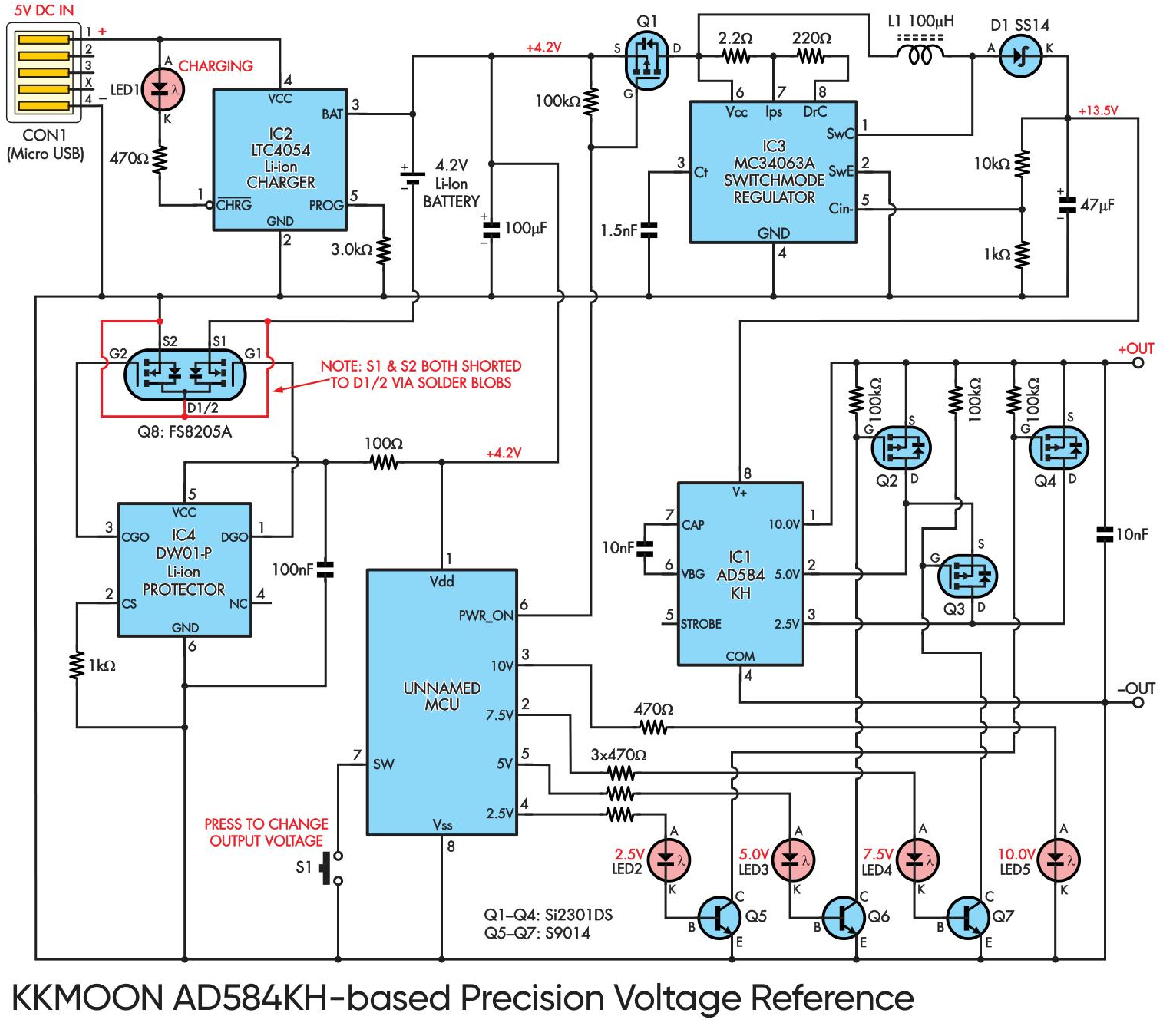

5V DC IN
CON1
(Micro USB)
CHARGING
LED1
470Ω
IC2
LTC4054
Li-ion
CHARGER
VCC
BAT
CHRG
PROG
GND
3.0kΩ
+4.2V
4.2V
Li-Ion
BATTERY
100µF
100kΩ
Q1
2.2Ω
220Ω
L1 100µH
D1 SS14
IC3
MC34063A
SWITCHMODE
REGULATOR
Vcc
Ips
DrC
SwC
SwE
Cin-
Ct
GND
1.5nF
+13.5V
10kΩ
1kΩ
47µF
Q8: FS8205A
S2
S1
G2
G1
D1/2
NOTE: S1 & S2 BOTH SHORTED TO D1/2 VIA SOLDER BLOBS
IC4
DW01-P
Li-ion
PROTECTOR
VCC
CGO
DGO
CS
NC
GND
1kΩ
100nF
100Ω
+4.2V
UNNAMED
MCU
Vdd
PWR_ON
10V
7.5V
5V
2.5V
SW
Vss
PRESS TO CHANGE
OUTPUT VOLTAGE
S1
IC1
AD584
KH
V+
CAP
VBG
STROBE
COM
10.0V
5.0V
2.5V
10nF
+OUT
–OUT
100kΩ
100kΩ
100kΩ
Q2
Q3
Q4
470Ω
3x470Ω
2.5V LED2
5.0V LED3
7.5V LED4
10.0V LED5
Q5
Q6
Q7
Q1–Q4: Si2301DS
Q5–Q7: S9014
KKMOON AD584KH-based Precision Voltage Reference

Fig.5: the circuit of the KKMOON voltage reference module is substantially more complicated, since it includes a DC/DC converter to boost the Li-ion battery voltage to a suitable level, as well as battery protection, a battery charger and output voltage selection via pushbutton S1.

Volt Ref.
AD584-
Agilent 34401A
2.500V
5.000V
7.500V
10.000V
2.50014
5.00292
7.50163
10.00393
2018

switch, while regulator REG1 derives a steady +12V to power IC1, the AD584LH. RF choke L1 and its associated capacitors ensure that the supply to IC1 is quite clean. LED1 provides a power-on indication.

Apart from the use of SMA sockets for the 10V, 5V and 2.5V outputs from IC1, the rest of the circuit is similar to that of the ML005 module.

However, there are two subtle differences, apart from the different AD584 version. One is that if you want a 7.5V output, this can be achieved by fitting a jumper shunt to SIL header P4. Then, SMA socket P1 delivers 7.5V rather than 10V.

The other difference is that the three main outputs of IC1 are also brought out to four-pin header P2, together with a ground connection. This may not seem significant, but it does make it easy to connect a voltage-trimming adaptor like that shown in Fig.4 to this module.

Trying them out

When we received the three modules, we put them through their paces. In each case, we applied power and allowed the module to warm up and stabilise for about one hour.

At the same time, we also switched on our very accurate Yokogawa 7562 6-1/2 digit DMM, and allowed it to stabilise as well. We then measured the four different DC voltage levels from each module, along with the noise levels, as shown in Table 2.

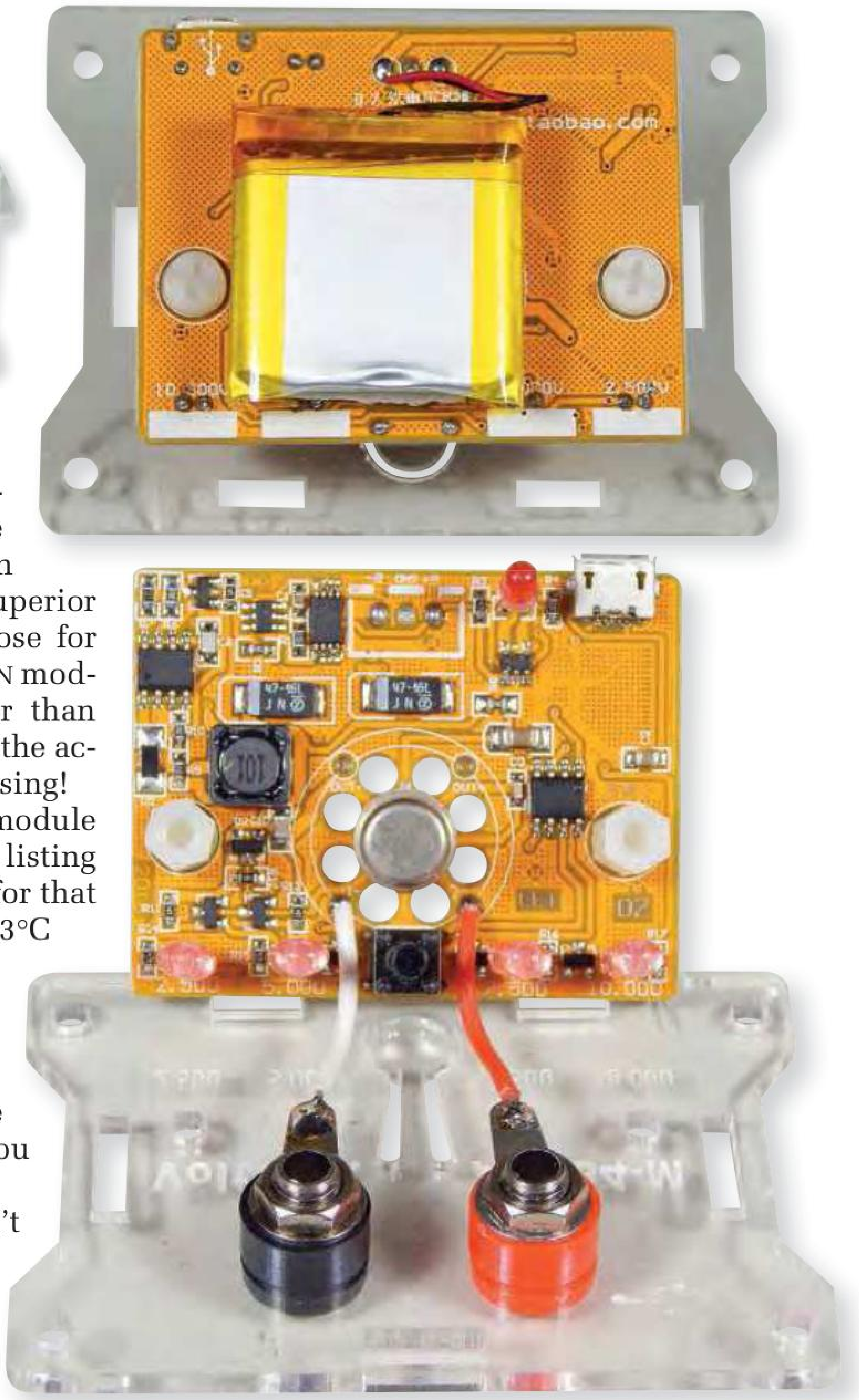
Overall, the output voltages from each module were within the specifications that were given by Analog Devices for the AD584 version used in that module.

In fact, the measured output voltages from all three modules were all within the specs given for the superior AD584LH device, with those for the ML005 and the KKMOON modules actually tighter/better than those for the module using the actual AD584LH. How surprising!

The box for the KKMOON module came with a stick-on label listing the actual output voltages for that module as measured at 23°C using an Agilent 34401A DMM. These were shown as 10.00393V, 7.50163V, 5.00292V and 2.50014V. Our measured figures were quite close to these, as you can see.

The ML005 module didn't come with any equivalent figures, but the module using the AD584LH device had a similar stick-on label on the sealed plastic bag it was packed in.

This 'high-precision' module did not state the meter that had been used to make the measurements, but they were shown as 10.004V, 7.503V, 5.003V and 2.501V; again within the AD584LH specs and also quite close to the figures we measured.



The KKMOON module has a LiPo cell mounted on the underside of the main PCB, which is held inside the acrylic case by two tapped spacers.

Our measurements for the noise levels from each module are somewhat higher than the AD584 specs would lead you to expect, although they're still quite low.

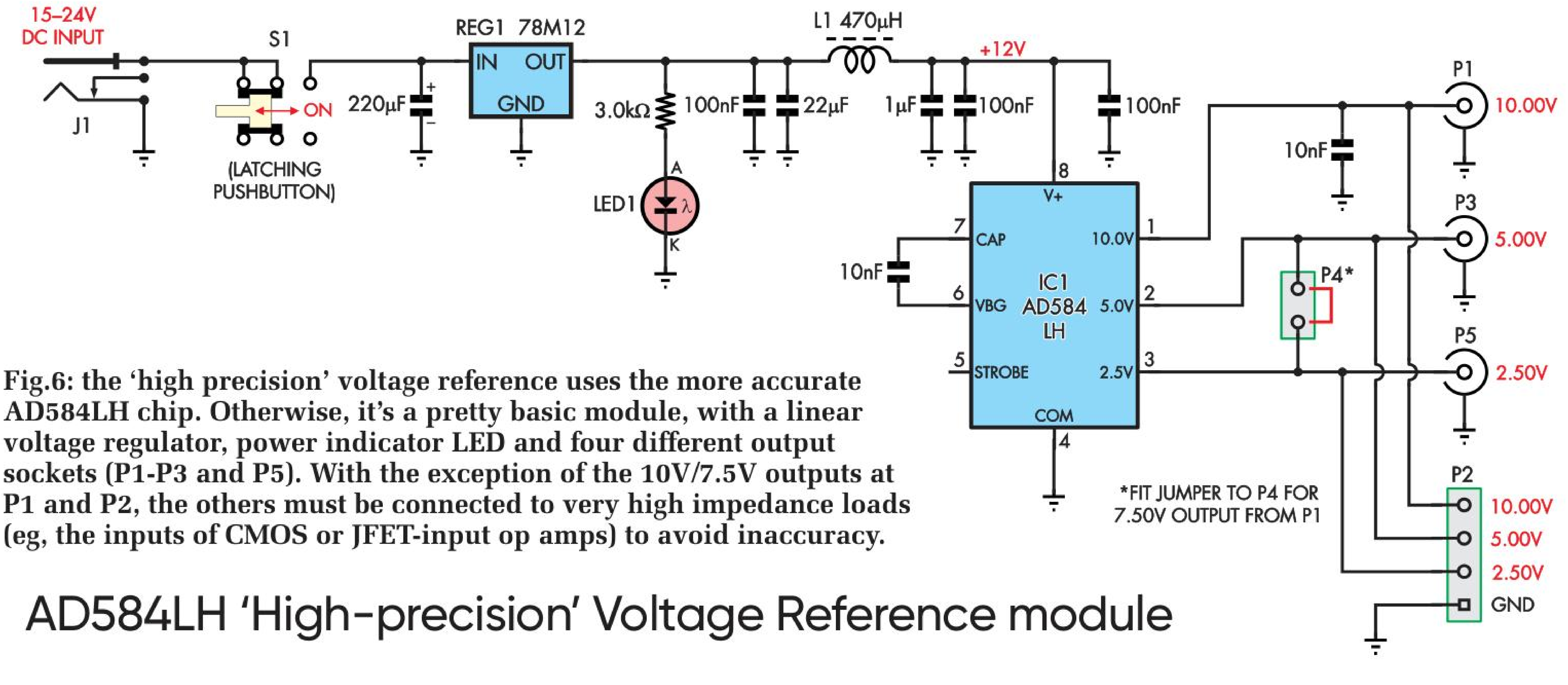

15–24V DC INPUT
J1
S1
ON
(LATCHING PUSHBUTTON)
220µF
REG1 78M12
IN
OUT
GND
3.0kΩ
A
LED1
K
100nF
22µF
L1 470µH
+12V
1µF
100nF
100nF
8
V+
7
CAP
10nF
6
VBG
5
STROBE
IC1
AD584
LH
10.0V
1
5.0V
2
2.5V
3
COM
4
10nF
P1
10.00V
P3
5.00V
P4*
P5
2.50V
P2
10.00V
5.00V
2.50V
GND
*FIT JUMPER TO P4 FOR 7.50V OUTPUT FROM P1
AD584LH 'High-precision' Voltage Reference module

Fig.6: the 'high precision' voltage reference uses the more accurate AD584LH chip. Otherwise, it's a pretty basic module, with a linear voltage regulator, power indicator LED and four different output sockets (P1-P3 and P5). With the exception of the 10V/7.5V outputs at P1 and P2, the others must be connected to very high impedance loads (eg, the inputs of CMOS or JFET-input op amps) to avoid inaccuracy.

This might be due to a shortcoming in the millivoltmeter used to make the measurements as its resolution below 1mV is rather poor.

We were interested to see if there was any adverse effect on the output stability or noise levels of the KKMOON module outputs as a result of its use of MOSFETs to control the output voltage and that high-frequency DC-DC boost converter, but we couldn't find any. The reference outputs of that module seemed to be just as stable and clean as those from the other two.

Trimming the AD584LH

The output measurements of the AD584LH-based module were a little disappointing, so we decided to try it out with a trimming adjustment adaptor. Fig.7 shows the adaptor circuit connected to the AD584LH module.

The components were fitted to a small piece of 'stripboard', with the 25-turn trimpot at one end and a 4-pin SIL socket at the other, to mate with pin header P2 on the module.

Using this simple adaptor we were able to adjust the 10.00497V output of the module down to 10.00003V at 26.4°C, with no increase in the apparent noise level.

It was then left operating undisturbed for four hours, during which the ambient temperature rose to 27°C and the measured output fell to 9.99997V – a drop of only 0.06mV or 60µV.

So our impression is that together with the trimming adaptor, the AD584LH module can be used to make a very stable and accurate voltage reference.

Which to choose?

If you just want a reference for checking 3-½ digit DMMs, analog meters and the like, the ML005 module would be ideal and has the price advantage over the other two modules.

But if you want a portable reference for checking instruments 'in the field', the KKMOON module would be the one to go for.

If you want the highest accuracy and stability, we'd suggest you choose the module based on the AD584LH device, together with the trimming adaptor circuit shown in Fig.7. This gives you a voltage reference comparable to commercial units costing over 10 times its modest cost of around £13.00.

You can find a quick overview of the same three modules over at: **www.markhennessy.co.uk/ad584_references/**

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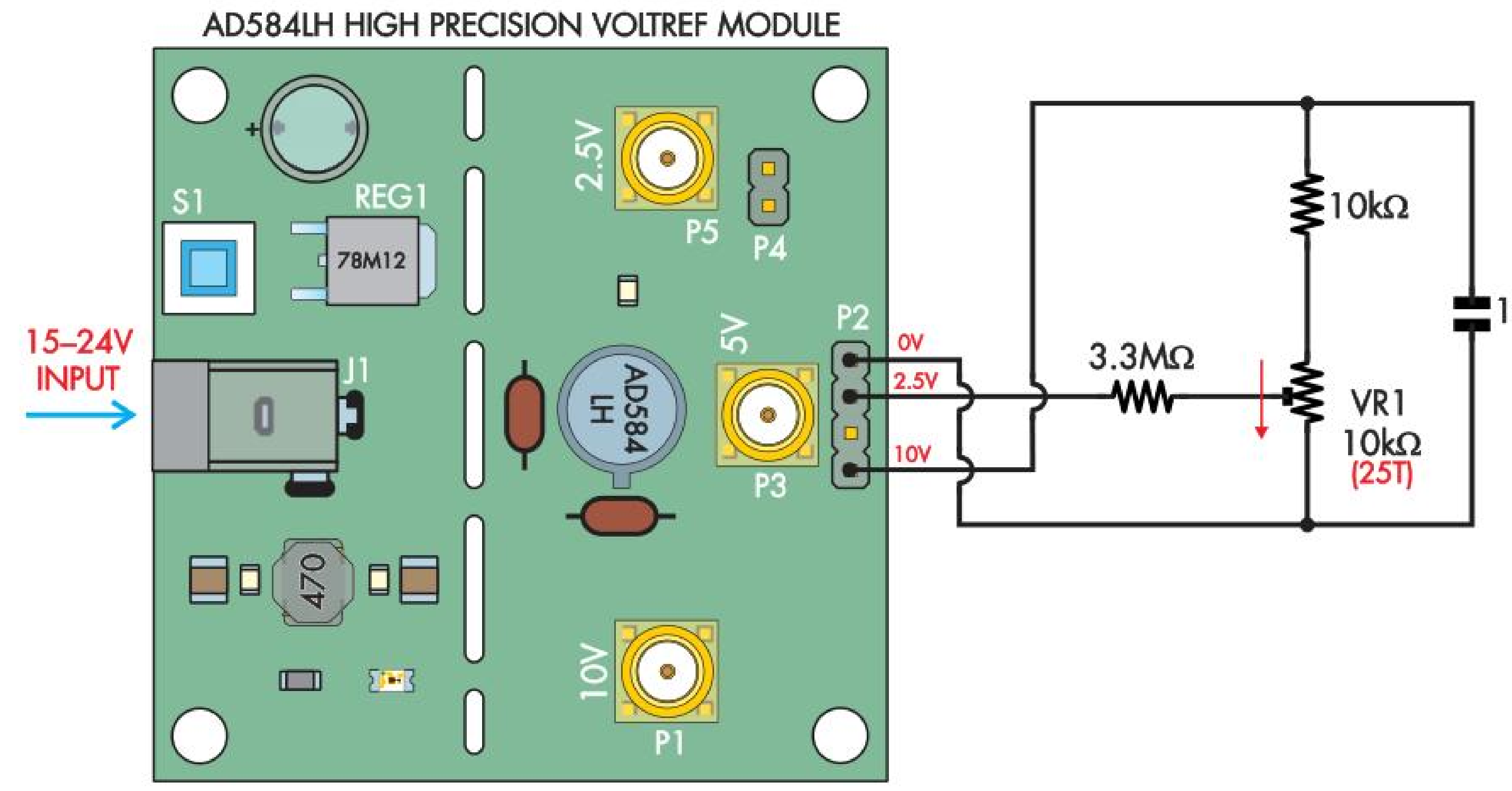


Trimming the AD584LH module output

Fig.7: the voltage reference can also be trimmed with the addition of just four components. As this is the most stable of the references described here, it would make sense to adjust it to be as close to the nominal voltages as possible. It should then remain accurate in the long term.

Table 1: basic specifications of the three main AD584 versions

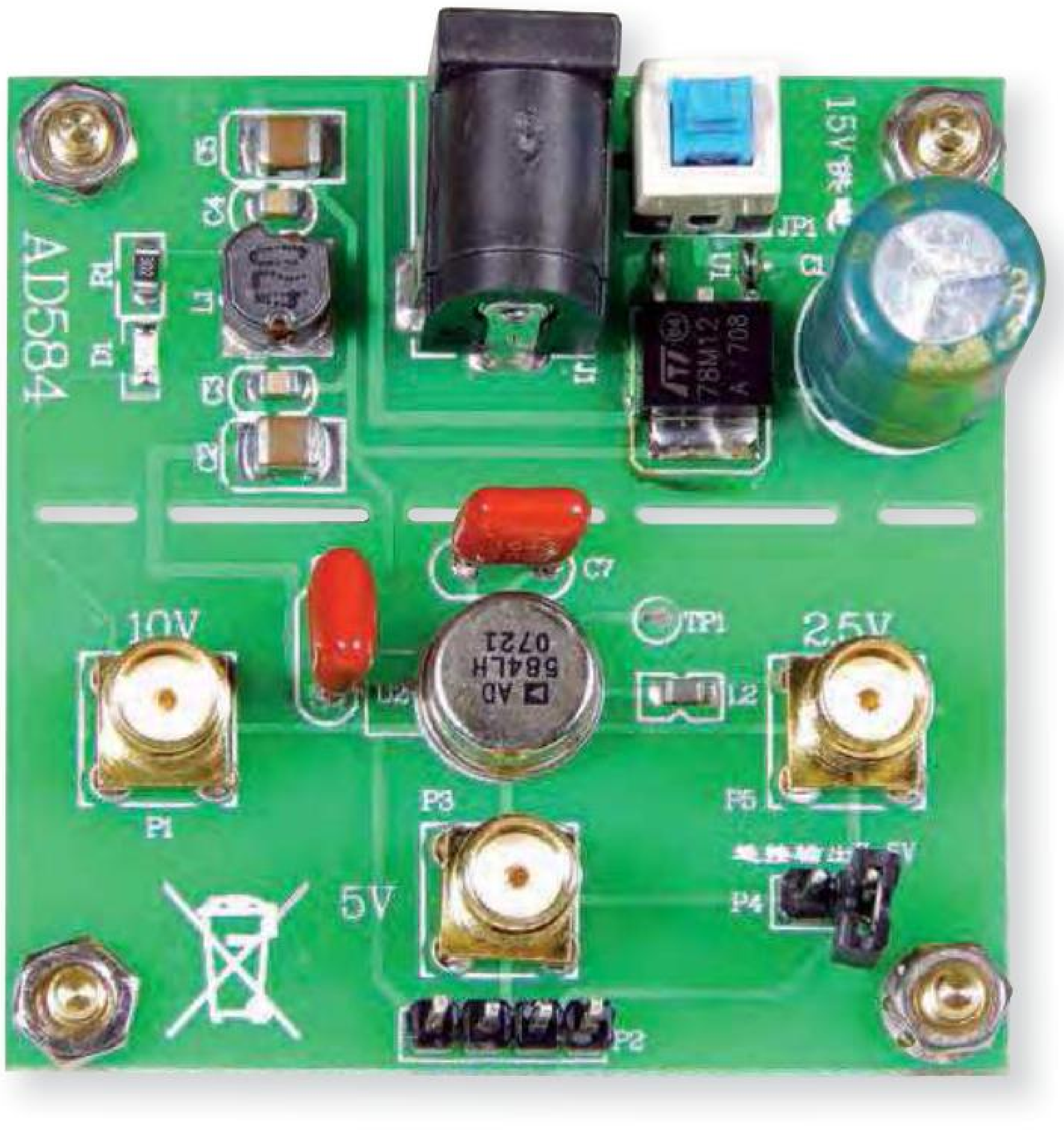
PARAMETER	AD584JH	AD584KH	AD584LH*
Maximum Error for Nominal 10.000V Output	±30mV at 25°C	±10mV at 25°C	±5mV at 25°C
Maximum Error for Nominal 7.500V Output	±20mV at 25°C	±8mV at 25°C	±4mV at 25°C
Maximum Error for Nominal 5.000V Output	±15mV at 25°C	±6mV at 25°C	±3mV at 25°C
Maximum Error for Nominal 2.500V Output	±7.5mV at 25°C	±3.5mV at 25°C	±2.5mV at 25°C
Temperature Coefficient (10V, 7.5V, 5V outputs)	30ppm/°C (Ref 25°C)	15ppm/°C (Ref 25°C)	5ppm/°C (Ref 25°C)
Temperature Coefficient (2.5V output)	30ppm/°C (Ref 25°C)	15ppm/°C (Ref 25°C)	10ppm/°C (Ref 25°C)
Noise Output (0.1–10Hz)	50µV peak-to-peak		
Long-term Stability (drift)	25ppm/1000 hours		

* Note: this version was discontinued by Analog Devices in 2012. Modules with it may use recycled ('aged') devices.

Table 2: Measured performance of three AD584-based voltage reference modules

Module (AD584 version, supply)	Voltage Setting	Measured Output	Error	Meas. Noise Output
ML005 (AD584JH, 15V DC supply)	10.0V	10.00269V	+2.69mV = +0.027% or +269ppm	< 0.7mV RMS
	7.5V	7.49998V	–0.02mV = –0.00027% or –2.7ppm	< 0.5mV RMS
	5.0V	5.00185V	+1.85mV = +0.037% or +370ppm	< 0.3mV RMS
	2.5V	2.49876V	–1.24mV = –0.0496% or –496ppm	< 0.3mV RMS
KKMOON (AD584KH, 13.5V DC supply)	10.0V	10.00364V	+3.64mV = +0.0364% or +364ppm	< 0.3mV RMS
	7.5V	7.50143V	+1.43mV = +0.019% or +191ppm	< 0.3mV RMS
	5.0V	5.00280V	+2.80mV = +0.056% or +560ppm	< 0.3mV RMS
	2.5V	2.50011V	+0.11mV = +0.0044% or +44ppm	< 0.3mV RMS
'Hi Precision' (AD584LH, 15V DC supply)	10.0V	10.00497V	+4.97mV = +0.0497% or +497ppm	< 0.3mV RMS
	7.5V	7.50342V	+3.42mV = +0.0456% or +456ppm	< 0.3mV RMS
	5.0V	5.00300V	+3.00mV = +0.06% or +600ppm	< 0.3mV RMS
	2.5V	2.50129V	+1.29mV = –0.0516% or +516ppm	< 0.3mV RMS

DC voltage measurements taken with Yokogawa 7562 6-1/2 digit DMM (warmed up for one hour), at 25.8°C and 62% RH



The alternative 'high-precision' AD584-based module. It uses an AD584LH as opposed to the AD584JH used in the ML005 module. However, when measured, this module displayed worse accuracy than the other two.

AM/FM/CW Scanning HF/VHF RF Signal Generator

Part 2

by Andrew Woodfield ZL2PD

We introduced this RF signal generator last month. It is an ideal entry-level test instrument for anyone into radio: capable, yet low in cost and quite easy to build. None of the parts are too hard to come by, either. . . Now let's get into building it – and getting it up and running. We also have some performance plots and instructions on how to use it.

The Signal Generator is built on one double-sided PCB coded 04106191, measuring 152.5 × 102mm, available from the *PE PCB Service*. Refer to the PCB overlay diagram, Fig.5.

Most of the top (component-side) surface has been retained as a ground plane for added shielding. No SMD parts are used in the construction of the *Signal Generator*, making it relatively easy to build.

Start by fitting all the resistors where shown. It's best to check each one with a DMM set to measure ohms before fitting them, as the colour bands can be hard to distinguish). Don't forget the 47Ω resistor hiding under S4.

Then mount diodes D1 and D2, ensuring they are oriented as shown. Next, mount IC1's socket with its notched end facing the top of the board.

Now fit the ceramic and MKT capacitors, which are not polarised. Don't get the different values mixed up though. There's also one of these under S4. Follow with trimpot VR1 and plastic package transistors Q1, Q2, Q4 and Q5. Q4 is a different type than the other three.

Next, solder 6-pin header CON3 and two-way headers CON4 and JP1 to the board, followed by the power socket (CON1) and then the electrolytic capacitors. These are polarised: the longer lead must go to the pad marked with a '+' on the PCB. The stripe on the can indicates the negative side.

Fit the three pushbutton switches, with the flat side oriented as shown in Fig.5, ensuring they are pushed down fully onto the board before soldering their pins. S3 is red while S1 and S2 are black. You now have almost enough components mounted to test the power supply.

It is recommended that you attach REG1 to the case for heatsinking, but we haven't built the case yet. Anyway, the easiest way to do this is to cut the three regulator leads short, then solder 25mm lengths of medium-duty hookup wire to the stubs, using some small diameter heatshrink tubing to insulate the solder joints and the lead stubs.

You can then solder these three leads to the regulator pads on the PCB, ensuring that it is soldered the right way around – ie, so that if you hold it up above the board with the wires not crossing over, the tab is facing away from the board, as shown in Fig.5.

Early testing

Now you can apply 12V power to DC input connector CON1 and make some checks. Unfortunately, there is no power-on indicator LED at this stage (there will be when MOD1 is fitted), so the simplest check is to measure the voltage at the right-hand pin of JP1 relative to a ground point such as the mounting screw hole in the middle of the board. At this stage, there should be little to no voltage.

Now briefly press power switch S3, and you should measure close to 5V on the right-hand pin of JP1. Press S3 again and that voltage should drop away to almost zero. That confirms that the power supply section is working correctly.

Modifying the AD9850 module

Minor modifications are required to the AD9850 module before mounting it on the PCB. Three SMD resistors need to be removed and a thin wire soldered to one of the free pads. These changes are shown in Fig.6 and the accompanying photo of the modified module.

The module I used is, I believe, the most-common version, but there appear to be other versions available that use the same circuit but a different layout. So if your module does not look exactly the same as mine, don't panic!

You can use a DMM set on continuity mode to identify the resistors connected to pins 3, 4 and 12 of the IC and then remove them.

You can do this by heating the ends of the resistors alternately with a soldering iron while holding the body of the resistor with tweezers. Once enough heat has been applied, you can lift it right off the board. If you have a hot-air rework station that makes it even easier.

It's then just a matter of soldering a 100mm length of light-duty hookup wire, or Kynar (wire wrap wire) to the now-empty pad which connects to pin 12 of the IC, as identified in the photo. This will be soldered to the main board later.

Winding coils L1-L3

The three inductors, L1-L3, are wound with 0.8mm diameter (26 gauge) enamelled copper wire. These are air-cored, meaning the coils are first wound around a suitably sized former, then the former is removed.

The coil diameters should all be 3mm, so a 3mm drill bit shaft or 3mm diameter metal tube would be suitable. The coil is then self-supporting when mounted on the PCB.

L1 and L3 need to be 160nH while L2 is 150nH. To achieve this, wind 11 turns for each coil, but then stretch L2 so that it is around 1mm longer than the other two. That reduces its inductance to the required value. (You could, of course, use an inductance meter to verify the coils if you have one).

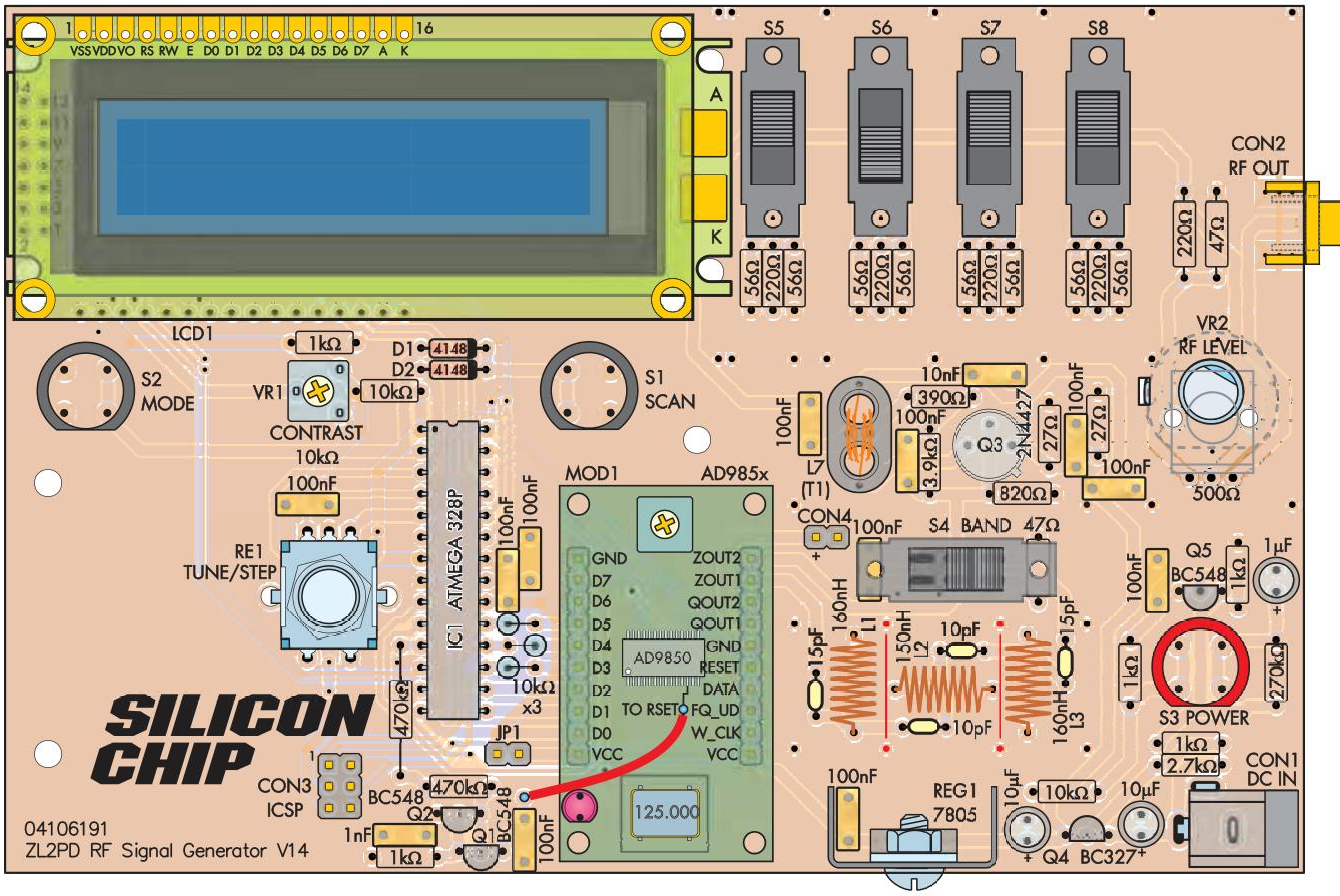

1
16
VSS VDD VO RS RW E D0 D1 D2 D3 D4 D5 D6 D7 A K
A
K
S5
S6
S7
S8
56Ω
220Ω
56Ω
CON2
RF OUT
220Ω
47Ω
LCD1
1kΩ
D1 4148
D2 4148
S2
MODE
VR1
10kΩ
CONTRAST
10kΩ
S1
SCAN
100nF
10nF
390Ω
100nF
3.9kΩ
Q3
2N4427
27Ω
100nF
27Ω
100nF
VR2
RF LEVEL
500Ω
L7
(T1)
820Ω
MOD1
AD985x
CON4
S4 BAND
47Ω
Q5
BC548
1kΩ
1µF
RE1
TUNE/STEP
IC1 ATMEGA 328P
GND
D7
D6
D5
D4
D3
D2
D1
D0
VCC
ZOUT2
ZOUT1
QOUT2
QOUT1
GND
RESET
DATA
FQ_UD
W_CLK
VCC
AD9850
TO RSET
125.000
160nH
L1
15pF
150nH
L2
10pF
10pF
15pF
160nH
L3
1kΩ
270kΩ
S3 POWER
1kΩ
2.7kΩ
CON1
DC IN
10kΩ
x3
470kΩ
JP1
SILICON CHIP
CON3
ICSP
BC548
Q2
470kΩ
Q1
BC548
1nF
1kΩ
04106191
ZL2PD RF Signal Generator V14
REG1
7805
10µF
10kΩ
10µF
Q4 BC327

Fig.5: use this overlay diagram as a guide to building the *Signal Generator*. We've shown both LCD screens in place here, (Jaycar QP5516 and Altronics Z7013; one on top of the other) but you would only fit one or the other. Edge connector CON2's middle pin is soldered on the underside of the board. VR2 can be a standard 16mm pot mounted through the board, with the body on the underside, or a 9mm vertical PCB-mounting type.

If you want to achieve the alternative inductor values mentioned last month, reduce the number of turns to six, then stretch L2 by around 0.5mm.

Now remove the enamel at each end of the remaining wire on each coil. Some enamel coatings vaporise while being tinned, but most must be scraped off with a sharp knife.

Take care if you use the latter approach, especially to avoid cutting yourself. You can verify that you've scraped off the insulation properly by tinning the wire ends and then checking that the solder has adhered.

But note that you don't want a lot of excess lead length on these coils; just enough to make it through the mounting holes on the PCB and be soldered on the underside.

So cut the wire ends to length before stripping the enamel.

Don't stretch or compress the coils to fit the pads on the PCB as this will affect their inductance; just use a short length of extra wire at one or both ends to reach the mounting pads.

Winding the transformer

T1 is wound on a 7mm-long ferrite balun core. Begin with 400mm of 0.315mm-diameter (28 gauge) enamelled copper wire.

Fold the wire in half so the two cut ends meet, then twist the two wires together to produce a twisted wire similar to that shown in Fig.7.

It can have anywhere from one to five twists every 20mm; this isn't critical. Twisting the wire simply makes winding the wire onto the core a little easier.

Wind four turns of the twisted wire onto the core and trim the ends of the 'bifilar' wires, so you have four short lengths of wire each about 20mm long appearing at one pig-nose end of the core.

Tin these four ends. Use a multimeter to identify the start and end of the two coils.

The start of one coil and the end of the other (shown as 'AS' and 'BF' in the diagram) go to the two central mounting pads for T1 (either together into one pad, or separately into each), while the other two wires go to the mounting pads at either end.

It doesn't matter which goes to which, as the coil is symmetrical.

Again, cut the leads to leave just a minimal amount and then strip the enamel off and tin them before soldering them to the board.

This should allow you to mount the balun close to the board, so it won't rattle around after the wires are soldered.

Proceeding with construction

Now fit metal-can transistor Q3 close to the PCB, leaving about 1mm between the bottom of the device and the upper PCB surface. Don't install it firmly down on the PCB because the metal case of the transistor is internally connected to the collector terminal of Q3.

Also, before you solder it in place, check the metal case is not touching any adjacent component leads.

Next, fit your modified AD9850 DDS module by soldering two 10-pin headers to the PCB, then soldering the module to the pins on top of these headers.

The wire you connected to that module earlier connects to the lead of transistor Q1 which is closest to MOD1. RevB PCBs have a dedicated pad for this wire.

Otherwise, solder it directly to Q1's lead, on the top side of the PCB. Either way, trim the wire to length before stripping and soldering it. This wire should ideally be routed under the module for neatness. If you keep it short, it won't move around later.

Next, fit output socket CON2. As it's an edge connector, push it onto the edge of the PCB, with the central pin sliding over the central pad on the bottom side.

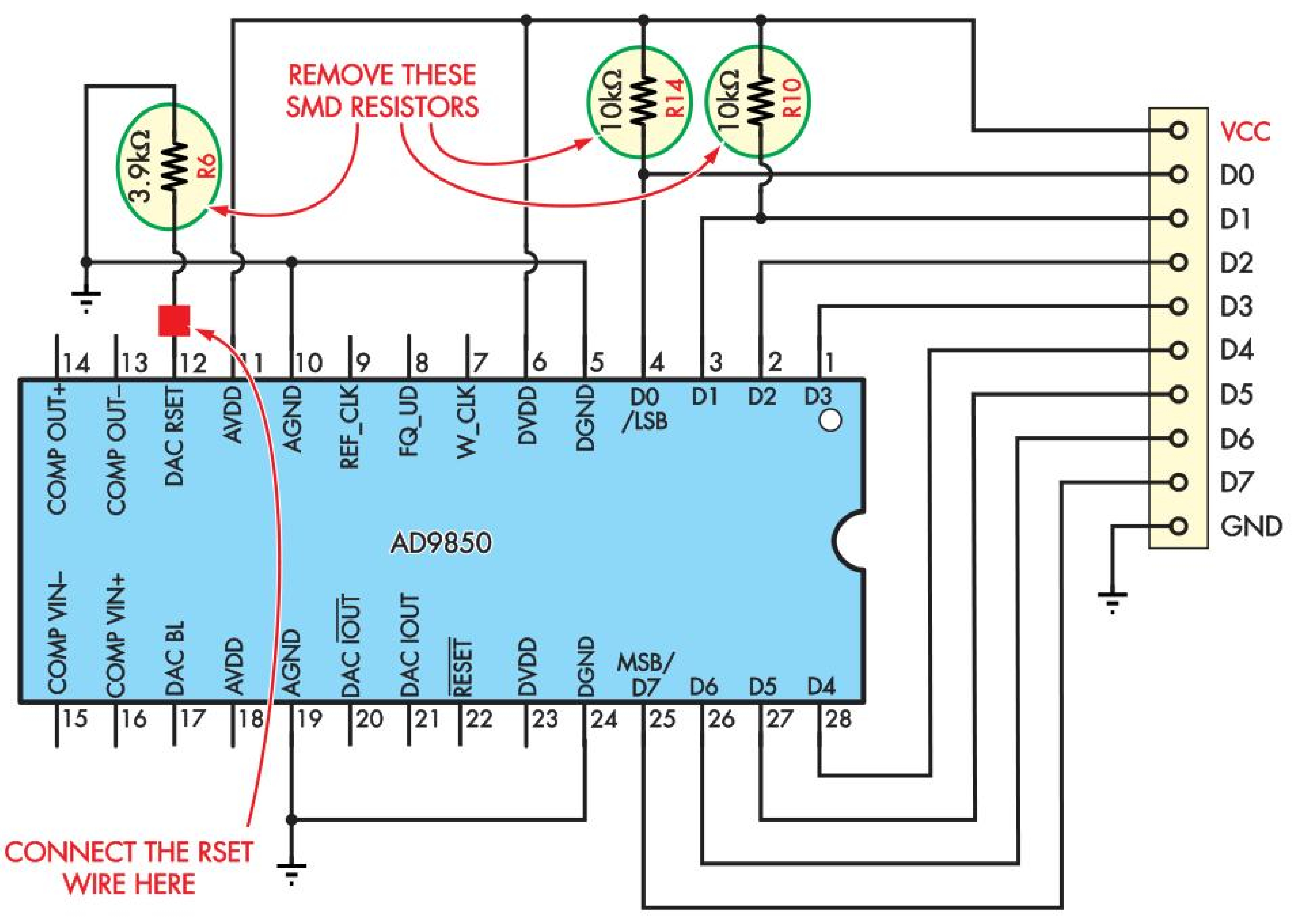
Solder that central pin, plus the posts on either side, on both the top and the bottom sides of the PCB.

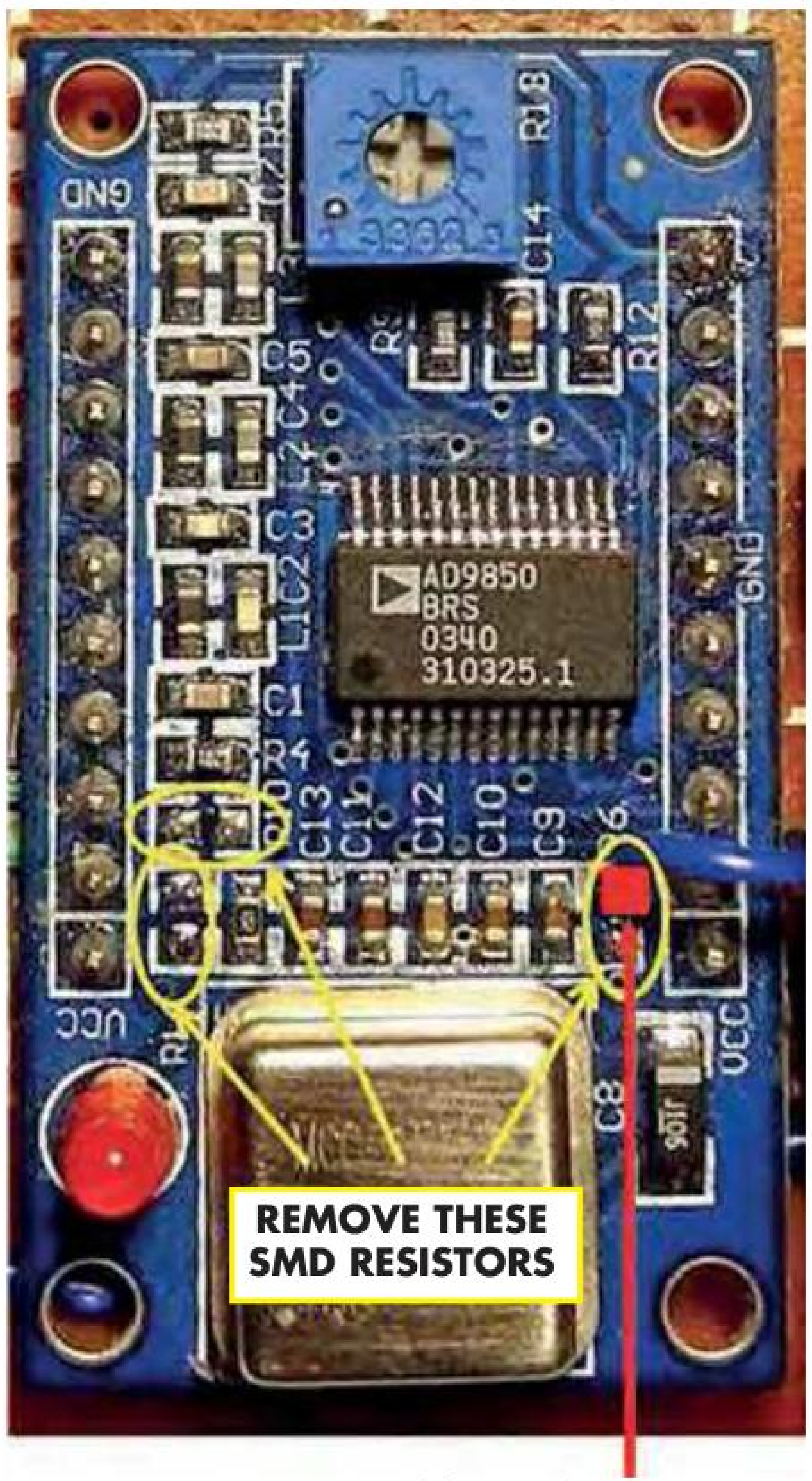
As this is a fairly substantial chunk of metal being soldered to copper planes, you will need a hot iron and be generous with the solder.

Then install mini slide switches S5-S9. The board is designed with slots to suit their lugs, so you can solder them right down onto the PCB. Again, be generous with the solder to ensure good joints.

Next, mount the LCD. There are three possible headers to suit different LCD module styles, although Jaycar QP5516 or Altronics Z7018 are the best fit.

For the Jaycar LCD, solder an 8×2-pin DIL header to the row of pins nearest the left edge of the PCB, then attach the four short tapped spacers to the corner mounting holes from the bottom of the board, using 5mm machine screws.


REMOVE THESE SMD RESISTORS
3.9kΩ
R6
10kΩ
R14
10kΩ
R10
VCC
D0
D1
D2
D3
D4
D5
D6
D7
GND
14
13
12
11
10
9
8
7
6
5
4
3
2
1
COMP OUT+
COMP OUT–
DAC RSET
AVDD
AGND
REF_CLK
FQ_UD
W_CLK
DVDD
DGND
D0 /LSB
D1
D2
D3
AD9850
COMP VIN–
COMP VIN+
DAC BL
AVDD
AGND
DAC IOUT
DAC IOUT
RESET
DVDD
DGND
MSB/ D7
D6
D5
D4
15
16
17
18
19
20
21
22
23
24
25
26
27
28
CONNECT THE RSET WIRE HERE


REMOVE THESE SMD RESISTORS

CONNECT THE RSET (PIN 12) WIRE HERE

Fig.6: these three SMD resistors must be removed from the AD9850 DDS module. One of the pads which connected to the now-gone 3.9kΩ resistor makes a handy connection point for the extra wire needed to connect pin 12 of the IC (RSET) to the collector of transistor Q1 on the main board, for output level control. See also the close-up photo at right.

You can then slip the LCD over the pin header and attach it using four more 5mm machine screws, then solder the header pins to the top of the LCD.

The procedure for the other LCDs is similar except some LCDs may require short jumper wires to connect to the PCB.

The final two components to fit are rotary encoder RE1 and potentiometer VR2. Mounting RE1 is easy; make sure it's perpendicular to the PCB and pushed all the way down before soldering its pins. Solder its five pins and two mounting lugs; you will need a hot iron for the latter, and be generous with the solder.

For VR2, we've provided two different options. The prototype used a 16mm potentiometer with its body on the underside of the PCB and its shaft passing up through a hole.

Mounting it in this way is a bit fiddly, but there are two benefits: this is a standard part that's easier to get, and its shaft will line up perfectly with pushbuttons S1/S2 and the access hole for trimpot VR1 (if provided).

Alternatively, if you can get your hands on a 9mm PCB-mounting right-angle potentiometer, it will be dead easy to mount to the PCB, as it's fitted similarly to RE1. However, due to the location of the hole for the 16mm pot's shaft, its shaft will sit around 3.5mm lower than S1/S2 and VR1. (This is hardly a tragedy – the choice is yours!)

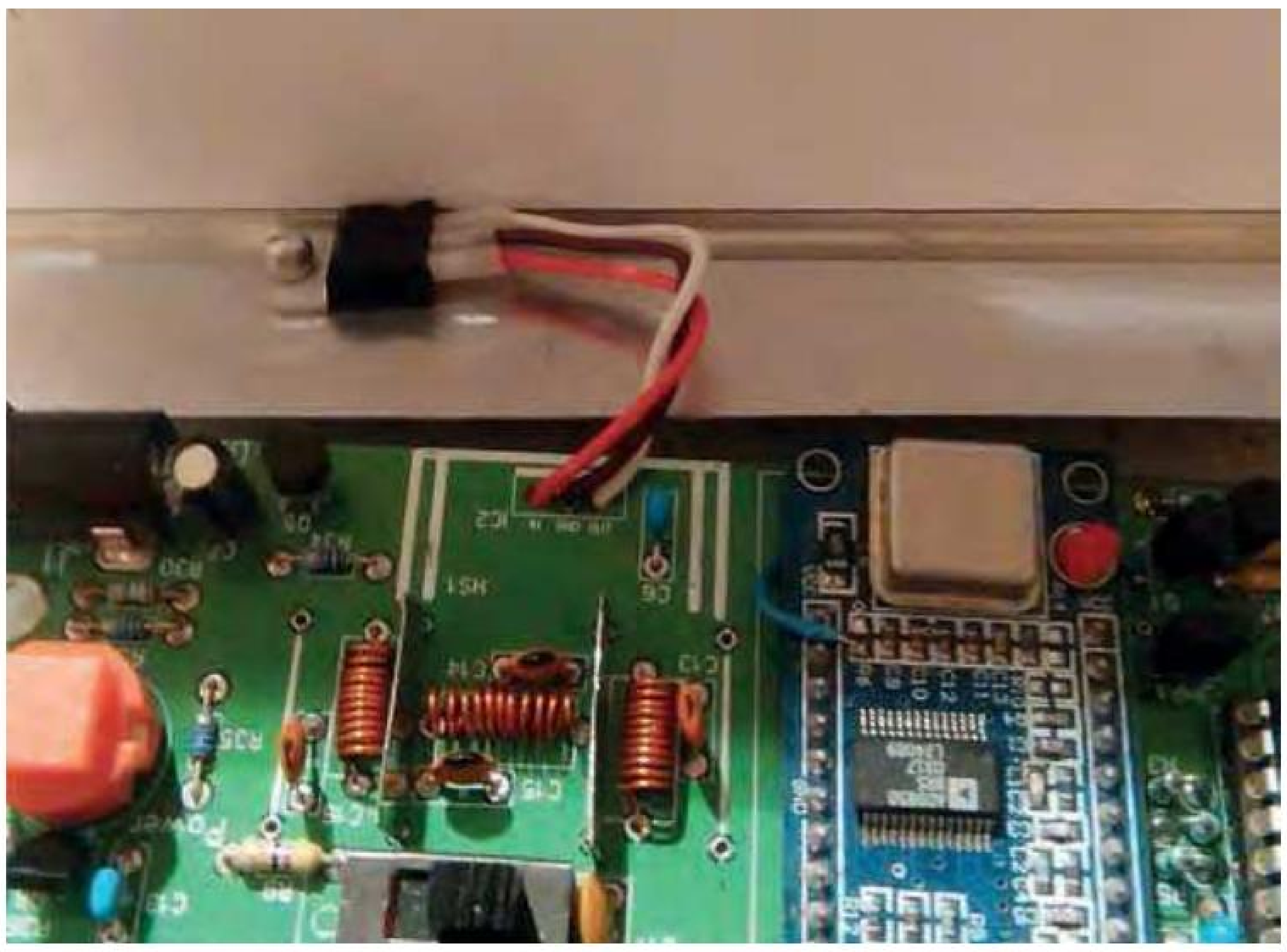
Now plug in the ATmega328 microcontroller (IC1), making sure its pin 1 is oriented correctly, towards the upper-left corner of the board. (If you haven't already programmed it or purchased a programmed chip, see the panel below detailing the programming instructions.)

Further testing

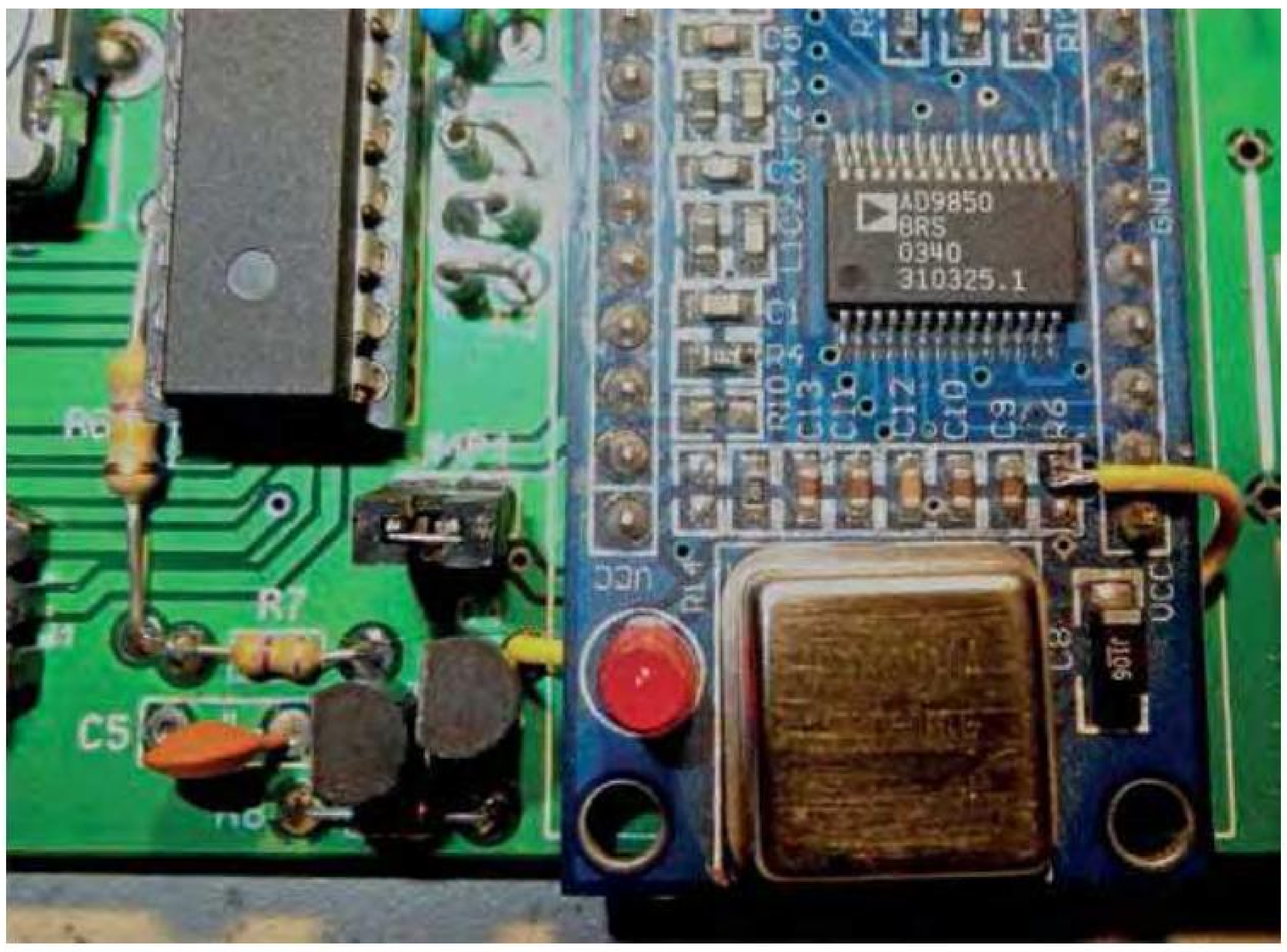
Later, we will be attaching REG1 to the metal case. However, since we haven't built it yet, for further testing temporarily attach a flag heatsink or attach it to a spare sheet of metal using a machine screw and nut.

You can now apply 12V power to CON1, press S3 and check that you can control the output frequency and amplitude (see the operating instructions below).

Power the unit down before finishing construction.



Two inter-coil screens, show in red on the overlay) must be fitted between the coils as shown here. These can be cut from a scrap of tinplate (eg, a food tin). This photo also shows the mounting of the 7805 regulator on the case heatsink.



The modified AD9850 module *in situ* on the main PCB. The three SMD resistors are all removed and the yellow wire is soldered to the appropriate pad – the one marked R6. (make sure it is the pad closest to the AD9850 IC).

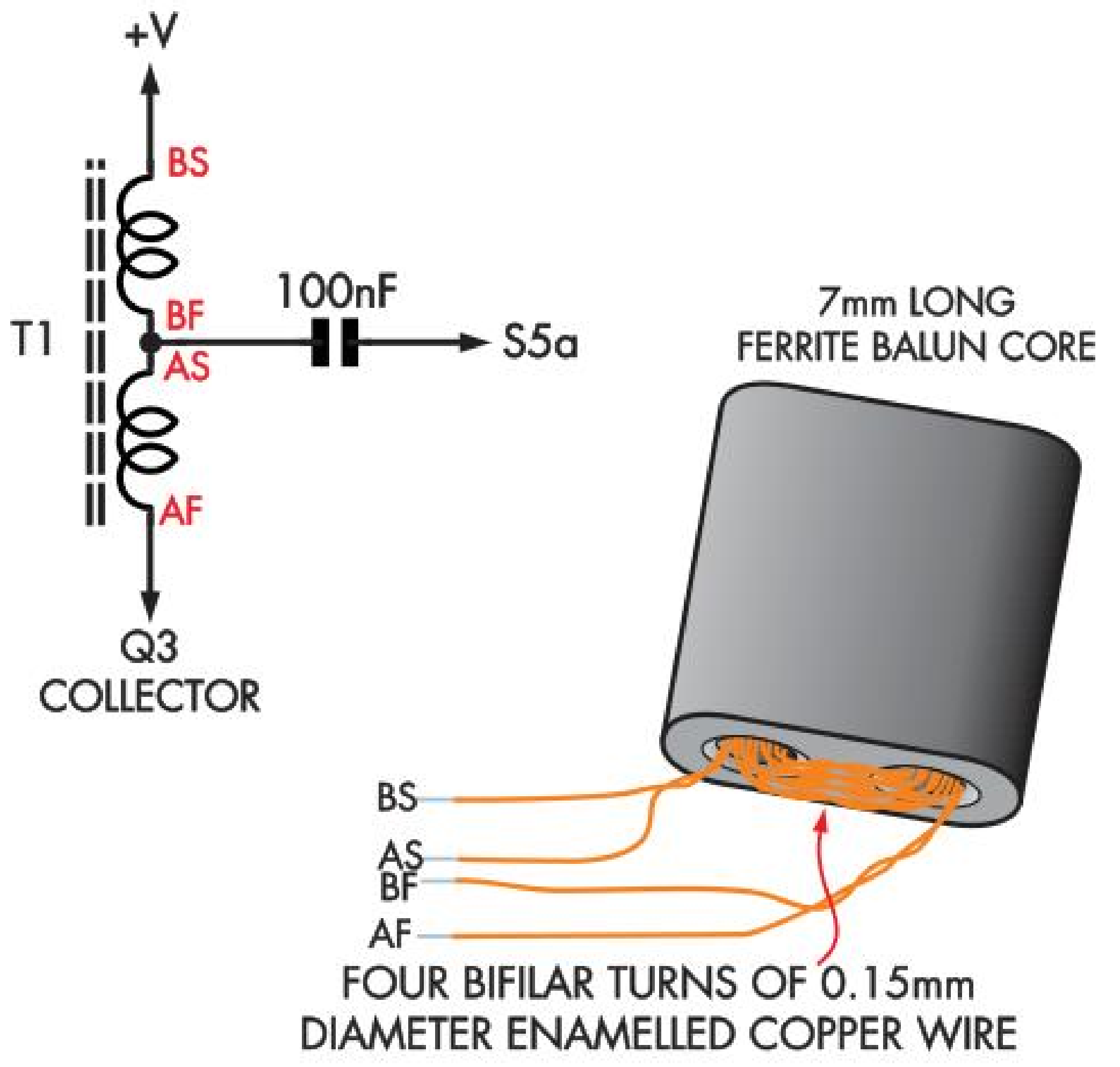


Fig.7: autotransformer T1 is easy to make, with just four bifilar turns wound on the small ferrite balun core. AF and BS are interchangeable and are connected together on the PCB.

Fitting the shields

You will notice several holes around the buffer, attenuator, output and band select/HPF sections of the board. There are also lines on the PCB 'silkscreen' between these holes. This is where shield plates can be fitted.

However, you do not need to fit shields in most of these areas; the only ones that are critical are those between the three high-pass filter sections (between L1 and L2, and L2 and L3).

So you only really need to cut two shield pieces and mount them using four posts in the holes provided. These are shown in red on the PCB overlay diagram, Fig.5.

Each shield piece should be around 8mm high and cut from 0.5mm tin plate, or recycled tin cans (a fruit or Milo tin lid is ideal).

The strips are then mounted to the board using component leads off-cuts soldered into the holes shown in red. This is simple yet effective.

You could fit shields in the other locations, but testing has shown that it makes virtually no difference to the device's performance so I don't feel that it's worth the time and effort to do so.

Making the enclosure

I couldn't find a suitable ready-made box for the *Signal Generator*, so I came up with a relatively easy way to make one.

It's a simple folded metal box and works well, resulting in a unit that is light but robust, compact and effectively shielded. Dimensioned drawings of the metalwork are available on the July 2020 page of the *PE* website – they're a little too large to publish here! The two panels are cut and folded from 0.8mm-thick aluminium sheets. The top cover and base may each be cut from a small 300 × 250mm sheet, making it relatively inexpensive to build.

Parts list – HF/VHF RF SIGNAL GENERATOR

1 double-sided PCB, coded 04106191, 152.5 x 102mm (from the *PE PCB Service*)
1 AD985x-based DDS module (MOD1)
1 PCB-mount barrel power socket (CON1)
1 SMA edge-mount socket (CON2)
1 2x3 pin header (CON3)
2 2-way pin headers (CON4)
1 jumper shunt/shorting block (JP1)
1 16x2 alphanumeric LCD with backlight (LCD1)
  [eg, Jaycar QP5521 or Altronics Z7018]
1 500mm length of 0.8mm diameter enamelled copper wire (for winding L1-L3)
1 400mm length of 0.315mm diameter enamelled copper wire (for winding T1)
1 7mm ferrite balun core (for T1) [Jaycar LF1222, Altronics L5235]
1 PCB-mount vertical rotary encoder with integral switch (RE1) [Jaycar SR1230] –
  IMPORTANT see below
1 28-pin narrow DIL socket (for IC1)
2 10-pin headers (for mounting MOD1)
1 16-pin SIL or 8 x 2 DIL header (for LCD)
4 6.3mm-long M3 tapped nylon spacers (for LCD)
8 5mm M3 panhead machine screws (for LCD)
2 black PCB-mount momentary pushbuttons (S1,S2)
  [eg Jaycar SP0721, Altronics S1096]
1 red PCB-mount momentary pushbuttons (S3) [Jaycar SP0720, Altronics S1095]
5 DPDT mini slide switches (S4-S8) [Jaycar SS0852, Altronics S2010/S2020]
1 9mm-diameter knob to suit VR2
1 28-34mm-diameter knob to suit RE1
1 0.5mm-thick tin plate or cleaned tin-plated steel cans
2 0.8mm-thick aluminium sheets, 300 x 250mm
1 adhesive panel label, 157 x 107mm
4 small self-adhesive rubber feet
Hookup wire, misc. enclosure hardware

Semiconductors

1 ATmega328P microcontroller programmed with 0410619A.hex, DIP-28 (IC1) – a
  programmed IC is available from: **www.siliconchip.com.au/Shop/9/5056**
1 7805 5V 1A linear regulator, TO-220 (REG1)
3 BC548 NPN transistors, TO-92 (Q1,Q2,Q5)
1 2N4427 NPN RF transistor, TO-39 (Q3)
1 BC327 PNP transistor, TO-92 (Q4)
2 1N4148 small signal diodes (D1,D2)

Capacitors

2 10µF 50V electrolytic	1 1µF 50V electrolytic	
11 100nF 63V MKT	1 10nF 63V MKT	1 1nF 63V MKT or 50V ceramic
2 15pF 50V C0G/NP0 ceramic		2 10pF 50V C0G/NP0 ceramic

Resistors (all 0.25W 1% metal film)

2 470kΩ	1 270kΩ	5 10kΩ	1 3.9kΩ	1 2.7kΩ	5 1kΩ
1 820Ω	1 390Ω	5 220Ω	8 56Ω	2 47Ω	2 27Ω

1 10kΩ mini horizontal trimpot (VR1)
1 500Ω 9mm vertical PCB-mount or 16mm standard potentiometer (VR2)

Encoders: we have discovered that some rotary encoders look identical but work differently, resulting in erratic operation. The V14 firmware addresses this; by default, it works with pulse-type encoders. You can identify these by testing continuity across the two internal switches; if they are both always open when the encoder is at rest, it is a pulse type. With the level type, one or both switches may be closed at rest, depending on the encoder's rotation. If you have a level-type encoder and V14 software, solder a 100kΩ resistor from pin 28 of the Atmel chip to ground, on the underside of the PCB. That will change the software to work with level-type encoders.

This grade of aluminium is light enough to be cut and folded easily with hand tools, but heavy enough to form a sturdy box for the *Signal Generator*.

Several holes need to be drilled and cut into the panel for the controls, slide switches, regulator and the LCD. Aside from standard drills, a metal nibbling tool is ideal for cutting out the rectangular holes.

Final finishing during fitting can be completed with a fine file.

The completed PCB is mounted using spacers and 3mm machine screws. It's

Programming the ATmega328 micro

ATMEL 0936
ATMEGA328P-PU

You can purchase a pre-programmed microcontroller (see parts list). Alternatively, to program AVR family microprocessors, you need a programmer such as the USBasp (see **www.fischl.de/usbasp/** for details and drivers). This can be purchased online from many suppliers for a few pounds.

Suitable free software is available for Windows, Linux and iOS online. This description focuses on the Windows version.

You need to install the USBasp drivers and download programming software. For Windows, this includes:

eXtreme Burner
http://extremeelectronics.co.in/avr-tutorials/gui-software-for-usbasp-based-usb-avr-programmers/

AVRDUDESS
http://blog.zakkemble.net/avrdudess-a-gui-for-avrdude/)

Khazama
http://khazama.com/project/programmer

Plug it in and complete the installation of the USBasp programmer into your PC. If you have the option of 3.3V or 5V programming levels, select 5V.

Launch the programming software you downloaded earlier and set the target device to 'ATmega328' or 'Atmega 328P', depending on your chip. Both may be used. Now download the HEX file for this project from the July 2020 page of the *PE* website (if you don't already have it) and select it as the file to be used to program the chip in your software.

Make sure JP1 has not been fitted to your signal generator board; if it has, remove it now. Note that since some of the ATmega328 pins connect to the AD9850 module, the AD9850 module's power LED will still light up and flash while the programmer is connected and running, despite having removed JP1 and therefore cut the power supply to the module. This is of no concern.

Plug the six-pin connector from the USBasp programmer into CON3 on the signal generator PCB, making sure that pin 1 on the programmer cable lines up with the pin 1 indicator on the PCB.

Now select 'Write FLASH buffer to chip' or 'Write – Flash' to program the ATmega328 with the HEX file. The LEDs on the USBasp will blink furiously for a minute or two while the HEX file is loaded into the ATmega328. A bar graph may be displayed in some cases on the PC screen, to show progress.

You then have to program the ATmega328 internal 'fuses'. These configure the operating characteristics of the ATmega328 to suit the software being run on the device.

For this step, insert the following settings into the relevant Fuse page/section of the programming software, then click on 'Write' to send the data to the fuses:

Low byte: 0xE2
High byte: 0xD9
Extended byte: 0xFF
Lock byte: 0xFF

Since the processor and display are powered via the programmer, once programming is complete, the display will briefly show the start-up message and then the initial signal generator screen. At this point, you can unplug the programming cable from CON3 and place a shunt on JP1.

best to line it up with the holes in the lid to figure out exactly where it will sit in the case before marking and drilling out the three mounting holes in the base.

Alternatively, as in the prototype, the *Signal Generator* PCB can be held onto the front panel using the rotary encoder nut, although it would probably be better to attach using at least one tapped spacer too.

Small self-tapping screws are used to hold the cover to the base of the box. Once you've cut and bent the sheets, rivet or screw the 7805 regulator (REG1) onto the metal cover just before the final step of screwing the cover to the base.

The front panel artwork is shown in Fig.8. It can be printed and covered with self-adhesive plastic film.

Trim the front panel artwork to cut out the holes for the various controls and display and test-fit onto the completed metalwork.

The most reliable method to fix the artwork in place is to spray the rear side of the artwork with adhesive spray obtainable from most art shops. While tacky, press the panel artwork into place. Remove the rotary encoder nut

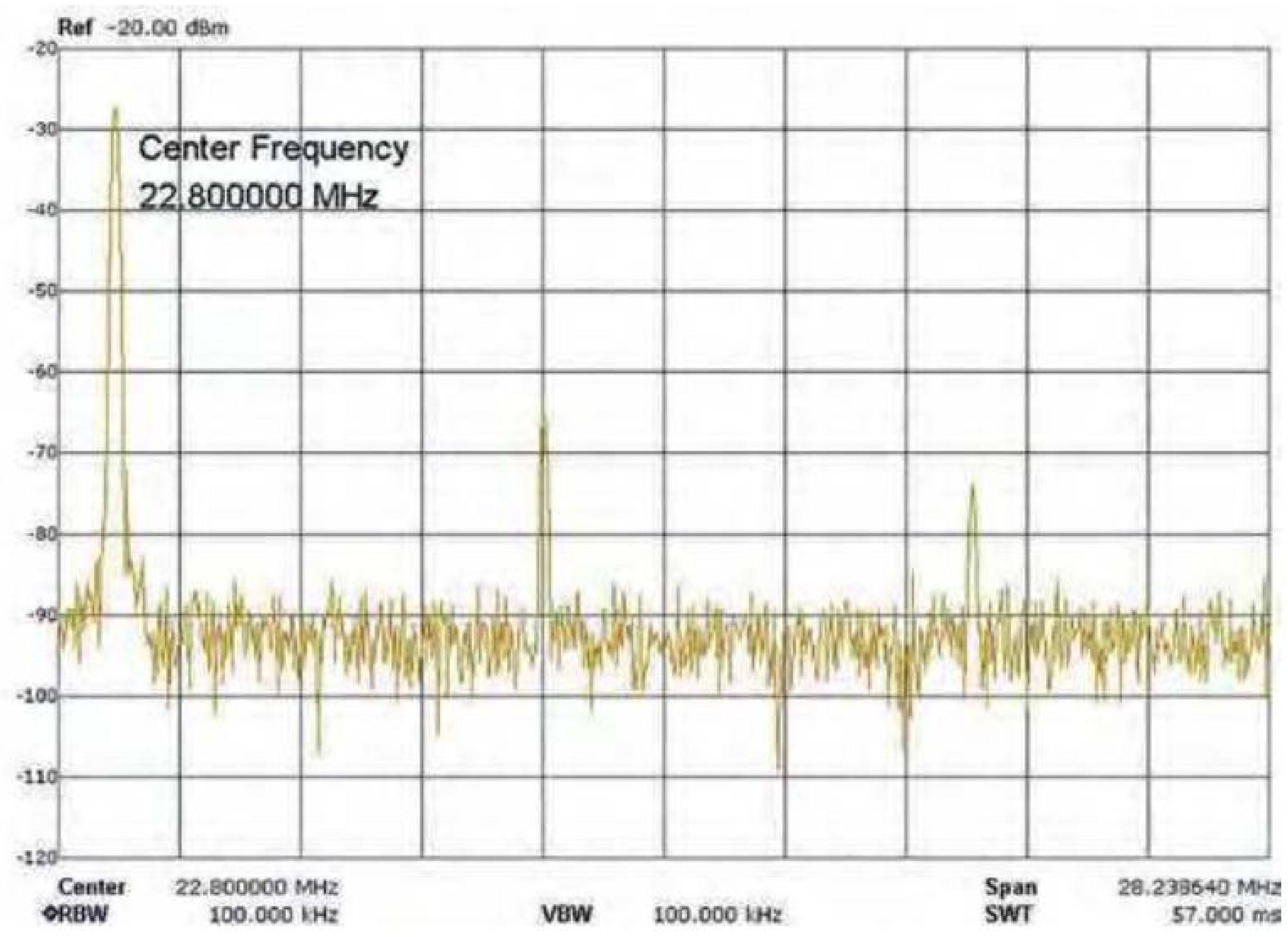


Fig.9: the CW (carrier wave, ie, unmodulated) output at 10MHz/–28dBm with a span of about 9-37MHz, selected to include the first two harmonics. This shows the second harmonic (20MHz) at around –40dB and the third (30MHz) at around –47dB.

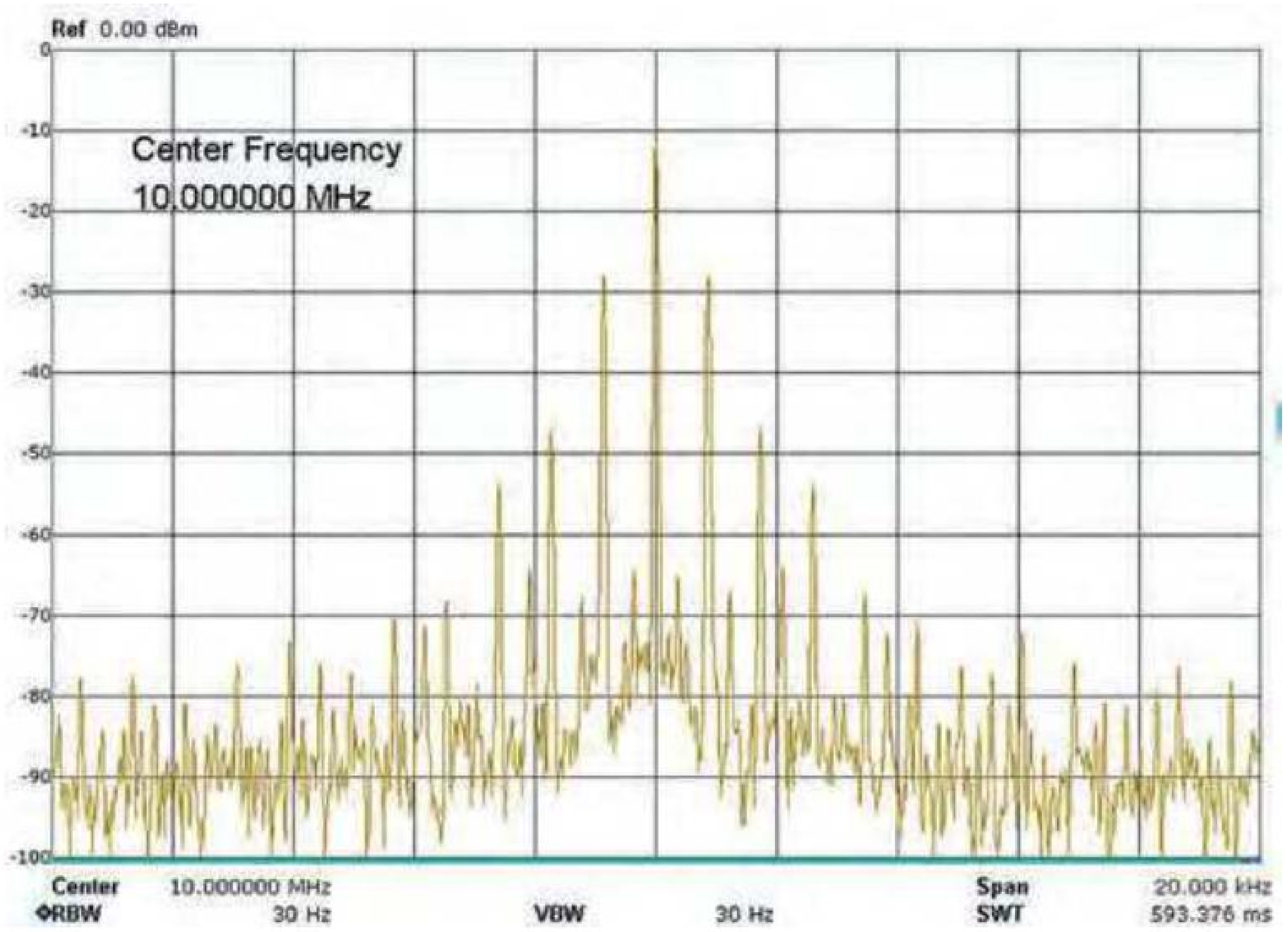


Fig.10: analysis of the AM output at 10MHz/–12dBm with a 20kHz span (ie, 9.99-10.01MHz). The 1kHz sidebands are visible either side of the carrier, as are the 1kHz modulation tone distortion products at ±2kHz (–21dB below the 1kHz fundamental) and ±3kHz (–26dB below the fundamental) indicating acceptable audio distortion levels. The modulation depth is the industry test standard, 30%.

before attaching the front panel, then reattach it on top.

3D-printed knobs

Suitable knobs may be available from normal suppliers. However, I designed the knobs for my *Signal Generator* using DesignSpark Mechanical and 3D-printed them from grey PLA filament.

My knob STL files can also be downloaded from the July 2020 page of the *PE* website for those wishing to print their own knobs. They press into place and hold securely.

It's useful to add four self-adhesive rubber feet to the rear of the metal enclosure. This prevents any sharp corners of the aluminium box from scratching the bench and helps to keep the oscillator in one place on the workshop bench.

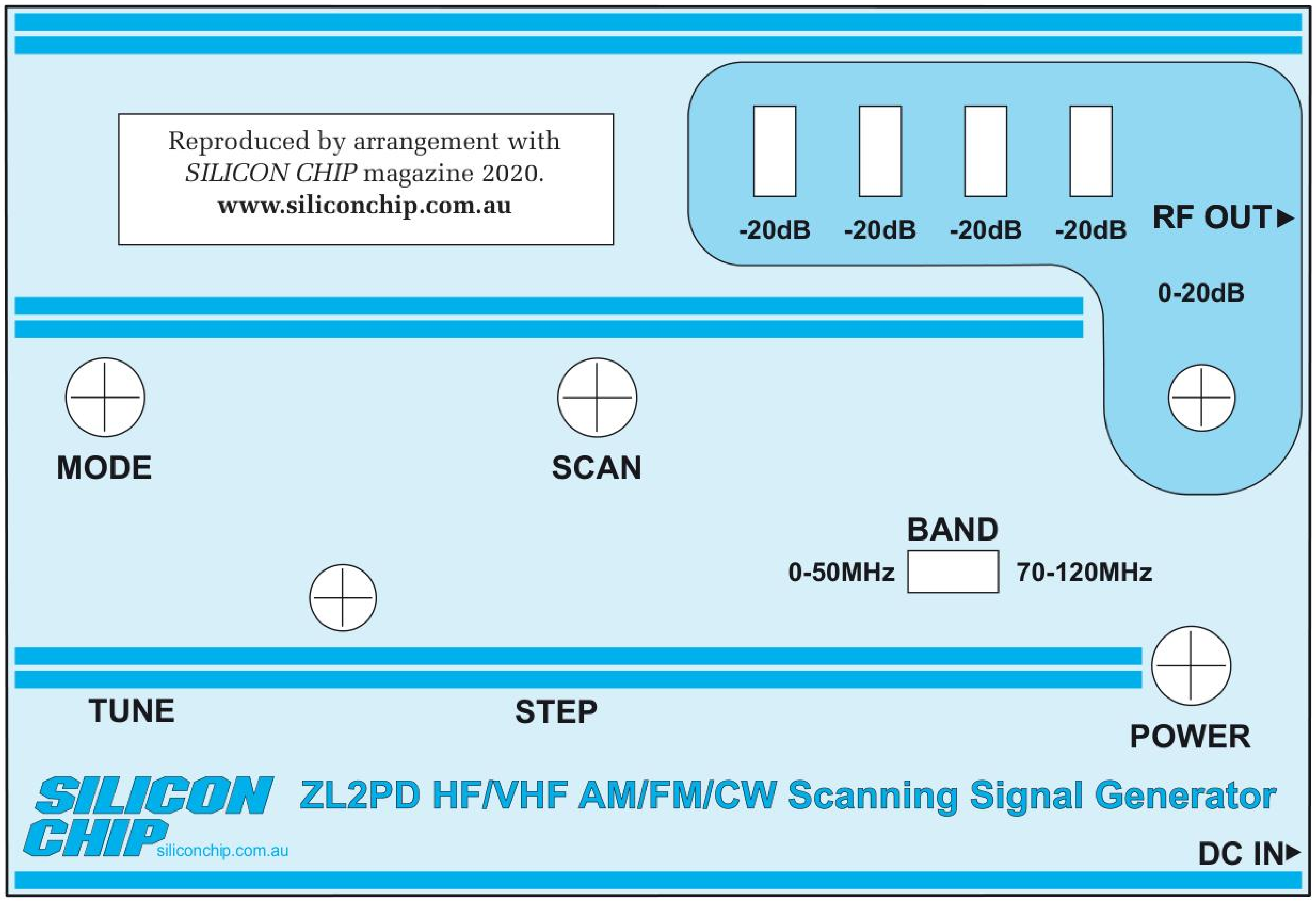


Fig.8: download this panel label from the July 2020 page of the *PE* website (as a PDF). Just print and laminate it, cut out the display and switch holes, then cut it to size and glue it to the outside top of the case.

Using the Signal Generator

Briefly press power switch S3 to turn the *Signal Generator* on. The display will show a start-up message, then after a short delay, the normal screen.

If you cannot see any text on the display, adjust VR1. This sets the LCD contrast. You can see examples of the various possible displays in the first article in this series, published last month.

The display shows the current output frequency and operating mode; the *Signal Generator* always starts at 10.000MHz in CW (unmodulated) mode.

The display also features a frequency 'dial' which covers a 1MHz span with 100kHz markers. As you rotate RE1 ('TUNE'), the output frequency changes and the cursor on this scale shifts across the 'dial'.

Pushing RE1's knob in (the 'STEP' pushbutton) changes the increments in which the frequency is adjusted with each click as RE1 is rotated. When you push this button, the underline below the LCD frequency display moves to indicate the current step setting.

The Band switch (S4) selects between the two output frequency ranges, 0-50MHz (left) and 70-120MHz (right), while S5-S8 at the top, in combination with VR2 at right, set the output amplitude.

The Band switch must be in the correct position for the currently selected frequency to get the expected output

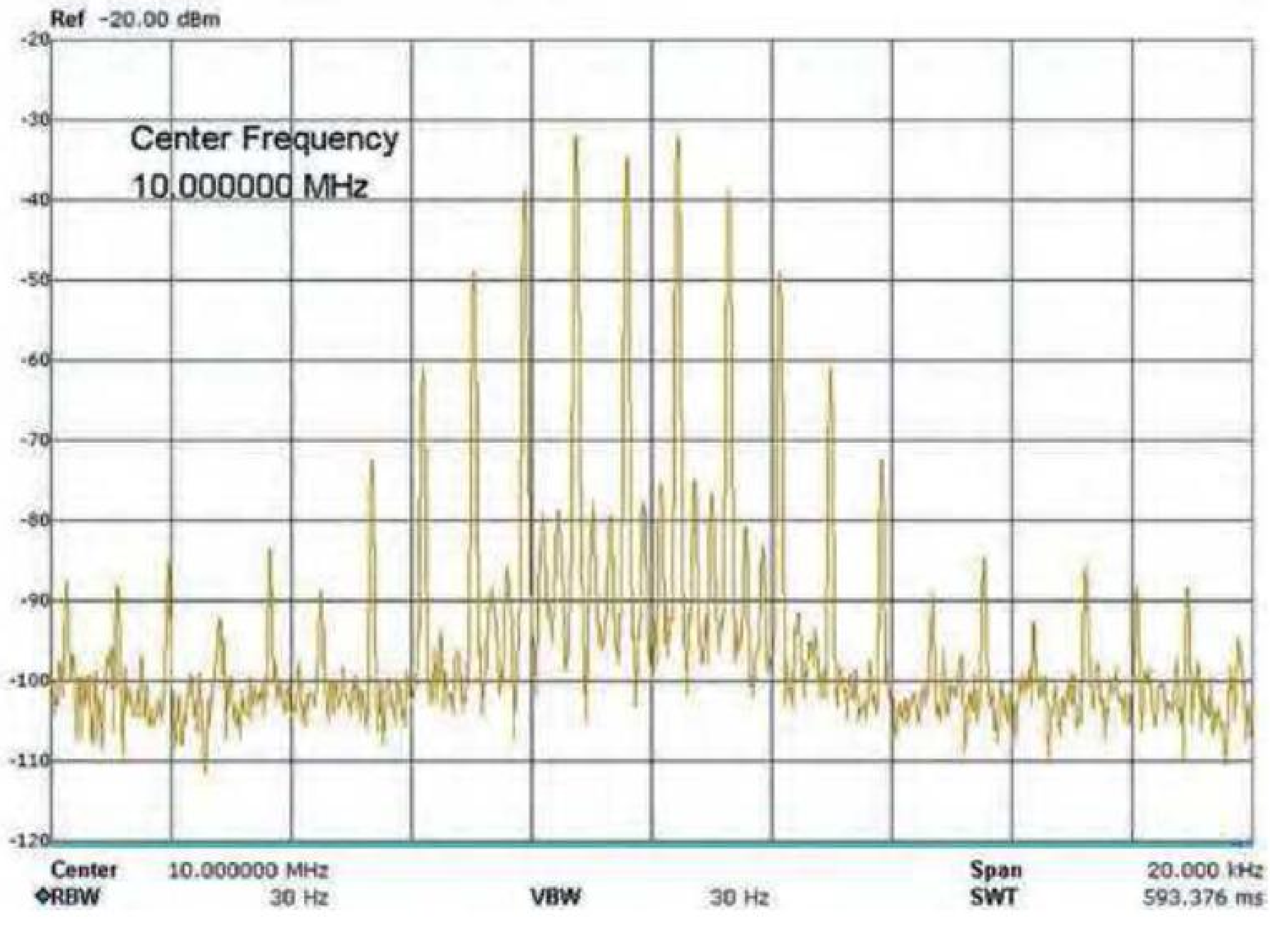


Fig.11: a 'narrow band' 1.75kHz frequency-modulated signal with a 10MHz carrier and a 20kHz span. The iconic equi-spaced 1kHz sidebands of a standard FM signal are clearly visible.

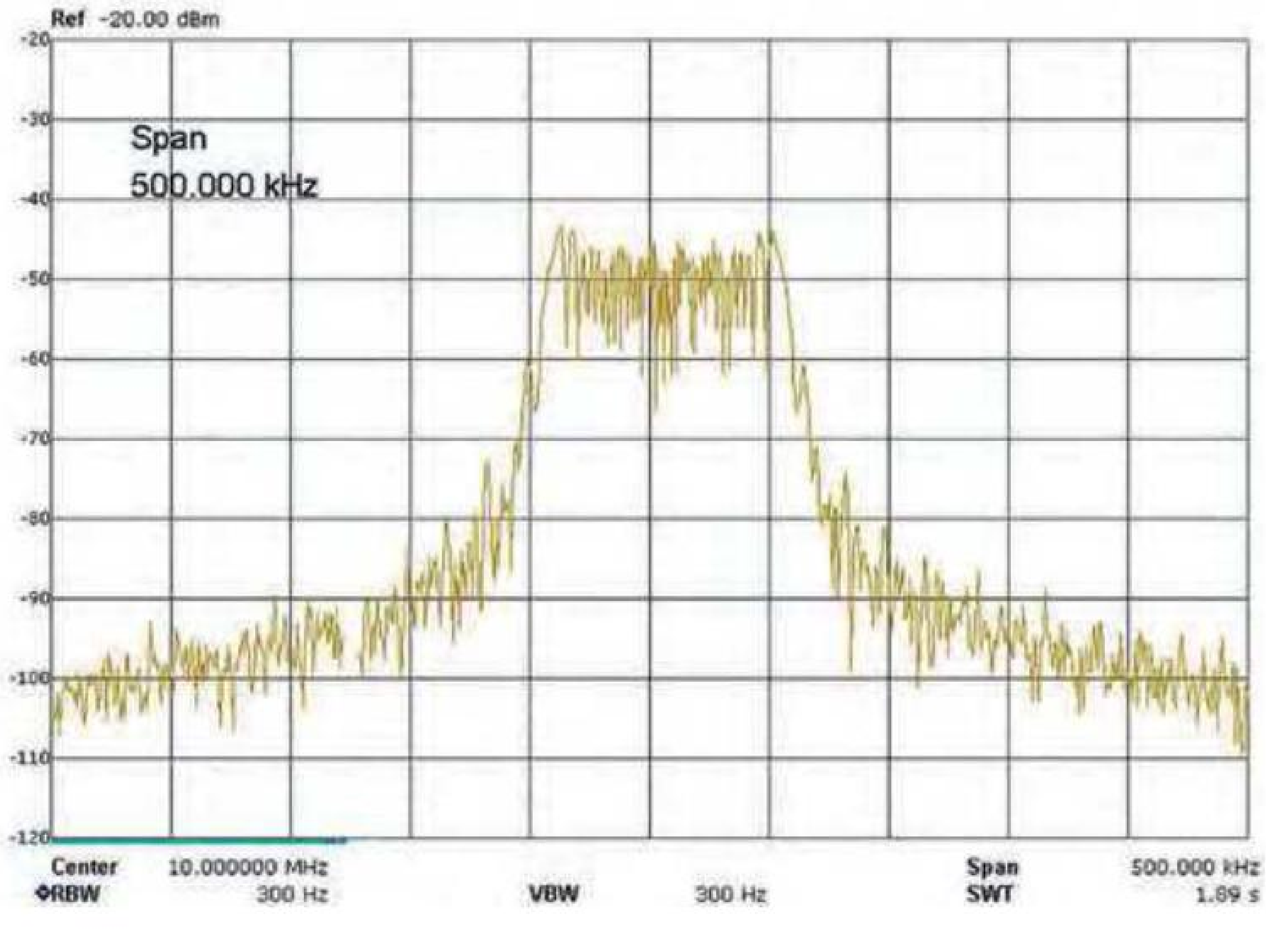


Fig.12: 'wideband' or broadcast radio-style FM, again with the carrier at 10MHz, this time captured with a 500kHz frequency span. This clearly illustrates that most of the signal energy falls within the 200kHz channel bandwidth permitted for broadcast FM signals.

amplitude. The HPF is very effective at minimising energy from aliasing below 70MHz, so the output level can be lower than expected by over 60dB if the incorrect selection is made. But no damage will occur as a result of an incorrect setting.

While the upper range is described as 70-120MHz, tuning and operation are maintained up to 150MHz, although output levels fall significantly above 120MHz.

The maximum output of +7dBm is with S5-S8 all in the up position and VR2 fully clockwise. For each 20dB of attenuation you need, switch one of S5-S8 into the down position (it doesn't matter which). Then for fine attenuation adjustments, rotate VR2.

For example, if you want –30dBm, set any one of S5-S8 down (+7dBm – 20dB = –13dBm) and then VR2 should be set quite low, to give an additional 17dB of attenuation. (Note: standard DDS amplitude rolloff impact above 30MHz – see Fig.3 in part 1.)

The *Signal Generator* mode is selected with brief presses of the Mode key (S2).

This selects between CW, AM, FM-NB (±1.5kHz deviation), FM-WB (±3kHz deviation), FM-BC (±50kHz deviation), or SCAN mode.

Pressing the Mode key again will select the initial CW (unmodulated) mode again, and the standard display screen.

Frequency scanning mode

If the SCAN mode is selected, the display changes to show the currently saved Start and End frequencies for the scan, and the number of steps selected. At power-on, this is set to 200 steps. If this is the first time after power has been applied, the default frequency settings (starting at 1MHz and ending at 30MHz) are shown. Otherwise, the last used settings will be displayed.

Pressing the Scan button again allows each parameter to be selected for adjustment.

Use the TUNE and STEP controls to set the Start and End frequencies in turn; here, the STEP button selects the tuning step as usual.

When the scan Steps parameter is selected with the SCAN button, the TUNE control has no effect, but pressing the STEP button allows the number of steps to be selected (10, 20, 50, 100, 200 or 500 per scan).

Finally, pressing SCAN again saves the selected values and starts the scan. The display now reports SCAN instead of the number of steps.

The scanning frequency increment is calculated by the processor using the entered values. The scanning speed is surprisingly fast.

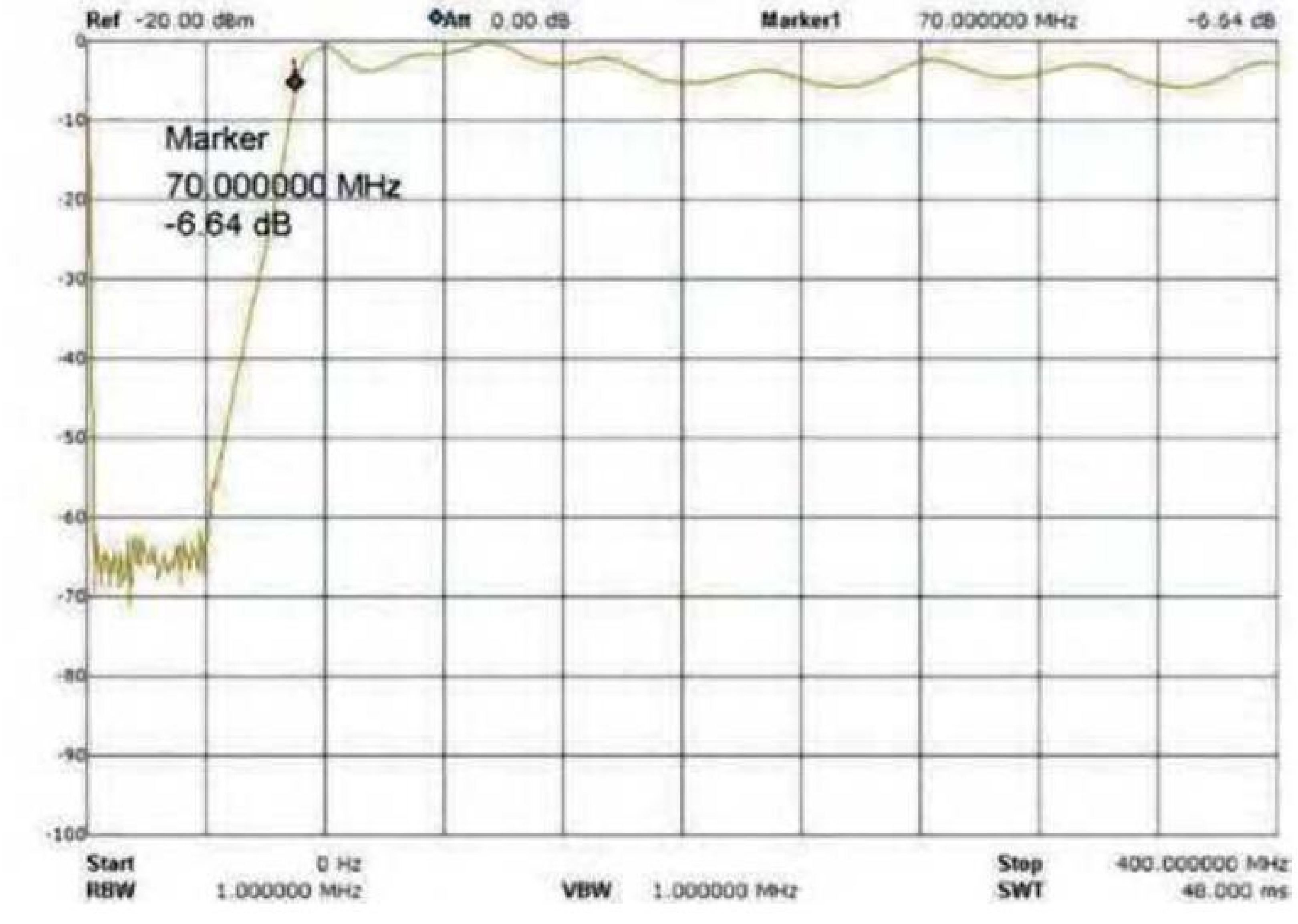


Fig.13: measured performance of the high-pass filter comprising inductors L1-L3 and four small ceramic capacitors. As you can see, the response is pretty much flat from 70MHz to 400MHz, but signals from 0-40MHz are attenuated by 60dB. The transition is smooth and quick, at around 75dB/octave, or 2dB/MHz.

Scanning may be interrupted and restarted using the SCAN key. When stopped, the Start and End frequencies, as well as the number of scan steps, can be adjusted again, and the scan restarted.

To exit the scan mode, press the MODE key. This also stops the scan and resets the *Signal Generator* to the last scanned frequency, and CW mode.

At each stage, the output can be checked with a suitable oscilloscope or with other RF test instruments.

Performance

Typical output signals from the *Signal Generator* are shown in Figs.9-12. These were captured using a Siglent 3GHz spectrum analyser. See the figure captions for details.

Fig.13 demonstrates how effective the high-pass filter is, despite being made from a self-wound air-cored inductors. This shows that the filter provides 60dB of attenuation for signals below 40MHz with a virtually flat passband from 70MHz up. The filter roll-off is quite steep at around 75dB/octave (the span from 40MHz to 70MHz is about 0.8 octaves).

Future possibilities

It is possible to add further features to the software. With the supplied software, less than 30% of IC1's program memory is used.

For example, RF output levelling would be possible, by using the pin 11 PWM output which drives the RSET pin of the AD9850 module (currently used to provide AM) to offset the sinX/X roll-off for frequencies up to about 50MHz, at the cost of a reduced maximum output level at lower frequencies.

Extended frequency coverage also appears possible through the use of alternative high-pass filters and/or by replacing the AD9850 module with one based on the pin-compatible AD9851.

Some minor additional software changes would be required to permit the AD9851 to be used. The AD9851 can be clocked at up to 180MHz, which may allow the generator to operate up to 100MHz in a single range, and possibly up to 300MHz with a modified HPF. Suitable AD9851 modules are available from the same sources as the AD9850-based module.

Adding other modulation modes such as FSK and BPSK is also feasible, but adding QPSK, for example, may be beyond the reach of this design.

Moving to an even more advanced DDS device, such as one based on the more modern AD99xx series chips, could be done. However, this would substantially increase the overall cost and complexity of the device.

It is also possible to replace the basic passive output variable attenuator network with a more elegant PIN-diode-based system.

This involves using components that are more difficult to obtain, but sufficient space has been left in this area of the PCB for such an addition.

Finally, you could consider adding a numeric keypad on the front panel to permit the direct entry of frequencies, tuning step and scan settings, plus you could add a settings memory for frequently used configuration.

However, this would likely require a processor change, or potentially even an additional microcontroller for handling keypad entry, to obtain the necessary spare I/O pins.

Having said all that, the design as presented is a good compromise between low complexity and cost, while still having a useful frequency range and a good set of features. It makes a great entry-level RF signal generator – a 'must' for anyone interested in radio at any level!

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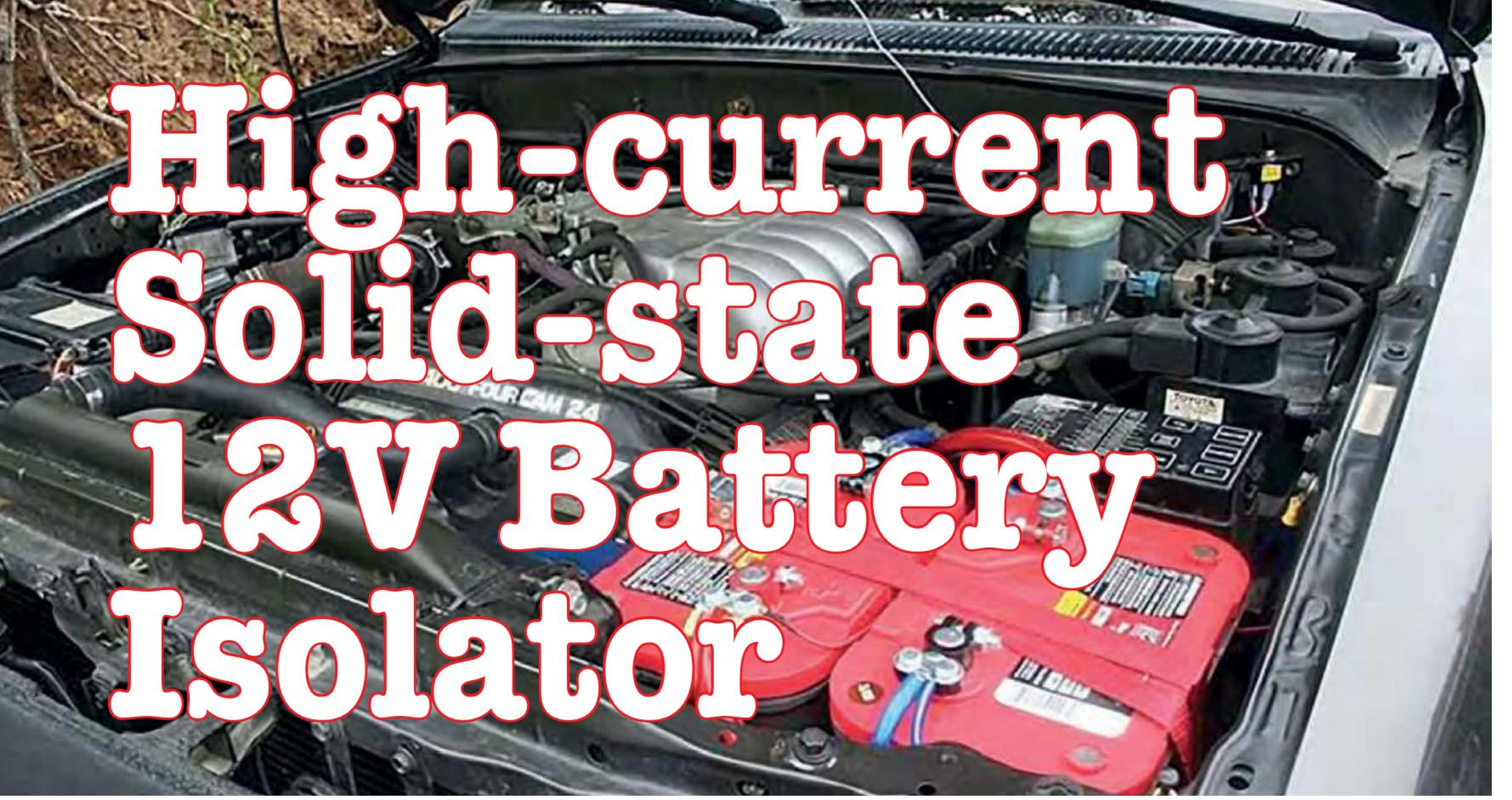

This device connects an auxiliary battery to the main vehicle battery/alternator while the engine is running, charging that extra battery. But it disconnects it once the engine shuts down, so that the vehicle battery can't accidentally go flat. It's cheap and easy to build but also very robust. It's ideal for RVs, campers, offroad vehicles and boats.

by Bruce Boardman (VK4MQ)

I have had ongoing problems with the battery systems on my 4WD vehicles. My car is fitted with an auxiliary 12V battery system that I use to run a fridge, some radios and camping lighting.

I tried using a commercial battery isolator to connect it to the main vehicle electrical system, but found that this had two major shortcomings.

First, its case offered little protection from the elements, and it occasionally filled with water – not good.

Second, it uses two open-frame-style relays to connect the batteries in parallel. The contacts in these relays are nothing special and occasionally weld together, leaving the batteries permanently connected. That can lead to both batteries going flat. Also not good!

The idea of these isolators is to parallel the batteries when the engine is running and remove this connection when the engine is off. So when you are camped overnight and you discharge the auxiliary battery, you can still start the engine in the morning.

It works by measuring the vehicle battery voltage, which is usually below 13V with the engine off and around 13.5-14.5V when the engine is running. So when the voltage is high enough, it determines that the alternator is charging the battery and connects the auxiliary battery. When the voltage drops, it detects that the engine has been stopped and breaks that connection.

Not being at all happy with the commercial units I tried, I decided to design my own. My design criteria were:

- Low current drain from the main battery when the engine is off.
- Fully solid-state operation (no relays).
- A low forward-voltage drop when switched on, minimising the heating and power loss.
- Must not interfere with radios (ie, no RFI/EMI).
- Must use commonly available parts.
- Must handle very high currents without damage (>100A).
- A completely waterproof and dustproof housing.

These made the first design decision easy: MOSFETs are an ideal solid-state switching device for large direct currents.

While P-channel MOSFETs are easier to drive for high-side switching, N-channel MOSFETs offer lower losses at the same price thanks to a vanishingly small 'on-resistance'.

So I chose six Infineon IRFS7434TRL7PP MOSFETs, which have an on-resistance of less than 1mΩ (0.001Ω) and are each rated at 40V and 362A. (I initially used similar IRFS3004-7PPBF devices in my prototype, but these have now been discontinued).

The S7434TRL7PP MOSFETs come in a 7-pin D2PAK (TO-263) SMD package with a large mounting tab, which serves as both the drain and thermal contact for the device, allowing heat to dissipate into the PCB. Despite the impressive specifications, these devices only cost round £2 each (from Mouser or DigiKey).

Circuit description

The circuit is shown in Fig.1. You can see the six power MOSFETs (Q1-Q6) at the top, between the two battery positive terminals. They are not all connected in parallel, for an important reason.

All power MOSFETs have an internal 'body diode' (also known as a parasitic diode or internal diode) which is an inherent part of their construction, and this allows current to flow in one direction even when the FET is switched off.

To prevent unwanted current flow in either direction, the six MOSFETs are arranged

Features and specifications

- **Suits most 12V batteries**
- **Waterproof**
- **Silent**
- **Solid-state (no relays)**
- **Easy construction and installation**
- **Switch-on voltage: 13.4V (13.13-13.67V*)**
- **Switch-off voltage: 12.6V (12.35-12.85V*)**
- **Quiescent current: approximately 3mA when off, 7mA when on**
- **High current handling (>100A peak, >40A continuous)**
- **Low voltage drop: typically <1mV/A**
  Low dissipation: typically <1W @ 30A

*if some ±0.1% resistors are used (see parts list)

as three pairs (Q1-Q3 and Q4-Q6), which are connected in 'inverse series'.

This way, the body diodes of each set of three MOSFETs are connected anode-to-anode and so block current flow in both directions, unless both sets of MOSFETs are switched on.

In this case, all the body diodes are effectively shorted out. Despite the FETs having very high current ratings, three have been paralleled in each set as cheap insurance against failure.

For example, the isolator could happen to be switched on during engine starting and starter motor currents can be very high, and high currents can also flow when the auxiliary battery is first connected to the vehicle electrical system after being fully discharged.

A single LM339 quad comparator (IC1) is used for all control functions. This contains four standard comparators with open-collector outputs, which go low when the voltage at the inverting (–) input is higher than the voltage at the non-inverting (+) input, and are high impedance the rest of the time.

That turns out to be quite useful in this circuit. I chose a switch-on threshold of 13.4V and a switch-off threshold of 12.6V. The main battery voltage is applied to pin 4 of CON1 and to a string of resistors to ground, which forms a voltage divider. The top part of the divider is 11.5kΩ [4.7kΩ + 6.8kΩ] and the bottom part is 6.8kΩ. This gives a division ratio of 2.69 [(11.5kΩ + 6.8kΩ) ÷ 6.8kΩ].

So at the switch-on battery-voltage threshold of 13.4V, that means that 4.98V is applied to pin 6 of comparator IC1b (very close to 5V), and at the switch-off threshold of 12.6V, pin 6 of IC1b sees 4.68V [12.6 ÷ 2.69].

A 5V reference voltage is supplied by linear regulator REG1, powered from the main battery via a 100Ω resistor, and this voltage is applied to pin 7 of IC1b, the non-inverting input. Initially, output pin 1 of IC1b is high, but once the main battery voltage rises above about 13.4V, the pin 6 input voltage exceeds that of pin 7 (ie, 5V) and so output pin 1 goes low.

This pulls current through the 4.7kΩ resistor and LED1, so LED1 lights up. In this condition, diode D4 is forward-biased and so the voltage divider formed by the 100Ω and 1.5kΩ resistors comes into play, reducing the voltage at pin 7 of IC1b from 5V down to about 4.69V (ie, 5V x 1.5kΩ ÷ [1.5kΩ + 100Ω]).

That has the effect of reducing the switch-off threshold to 12.6V (4.69V × 2.69) as desired. That prevents the unit from switching on and off rapidly if the battery voltage is near either threshold.

ON: 13.4V
OFF: 12.6V
SILICON CHIP
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MAIN
AUX
DUAL 12V BATTERY ISOLATOR

Shown here without its connecting leads (with their insulating covers, they'd hide half the panel!). Use of the *12V Battery Isolator* is simplicity itself: connect the 'main' terminal to the 'main' battery positive and the 'aux' terminal to the 'aux' battery positive, with a chassis connection provided through the diecast metal case secured to the vehicle. That's it! The LED will glow when the main battery voltage is high enough to charge the auxiliary battery.

The output voltage from pin 1 of IC1b is also fed to the pin 8 inverting input of IC1c, which has its pin 9 non-inverting input connected to the 5V rail, so it acts as an inverter.

So when the main battery voltage rises and IC1b's output goes low, IC1c's output goes high allowing the gates of the FET's to be pulled up via the 10kΩ resistor, switching them on (as described below) and connecting the two batteries.

REG1 is a micropower regulator, both to minimise the quiescent current but also (and most importantly) because it has an excellent initial tolerance of ±0.5%. This, along with the 1% resistor tolerances, determines how accurate the switch-on and switch-off voltage thresholds will be.

Note that if you change the battery sense voltage divider resistors, you can calculate the new switching thresholds by calculating the divider ratio, then multiplying 5V and 4.7V by this ratio.

To change the hysteresis (ie, the spread of these two thresholds), you would need to change the value of the 1.5kΩ resistor at pin 7 of IC1b; a lower value gives more hysteresis, and a higher value, less hysteresis.

MOSFET gate drive

To switch on an N-channel MOSFET, the gate needs to be driven several volts above the source. In this circuit, all the MOSFET sources are connected together and when the MOSFETs are switched on, they will all rise to the battery voltage – ie, around 12V.

Therefore, the gates need to be driven to at least 17V and ideally higher, to 20V or more, to ensure that they switch on fully and have the lowest possible resistance and dissipation. This voltage is generated by comparator IC1a, which is configured as an astable oscillator and drives a charge pump. The frequency of this oscillator is set to around 15kHz by the combination of the 22kΩ feedback resistor and 3.3nF timing capacitor.

Output pin 2 of IC1a is pulled high by a 4.7kΩ resistor, and the resulting square wave causes the 100nF capacitor to charge up to around 12V, via diode D2, when output pin 2 goes low.

When that pin goes high, to around 12V, the anode of diode D3 is lifted up to around 22V and this voltage in turn charges the following 100nF capacitor which supplies the MOSFET gates with about 20V via the following 10kΩ resistor. That is, as long as output pin 14 of inverter IC1c is not being held low. If it is, this shunts

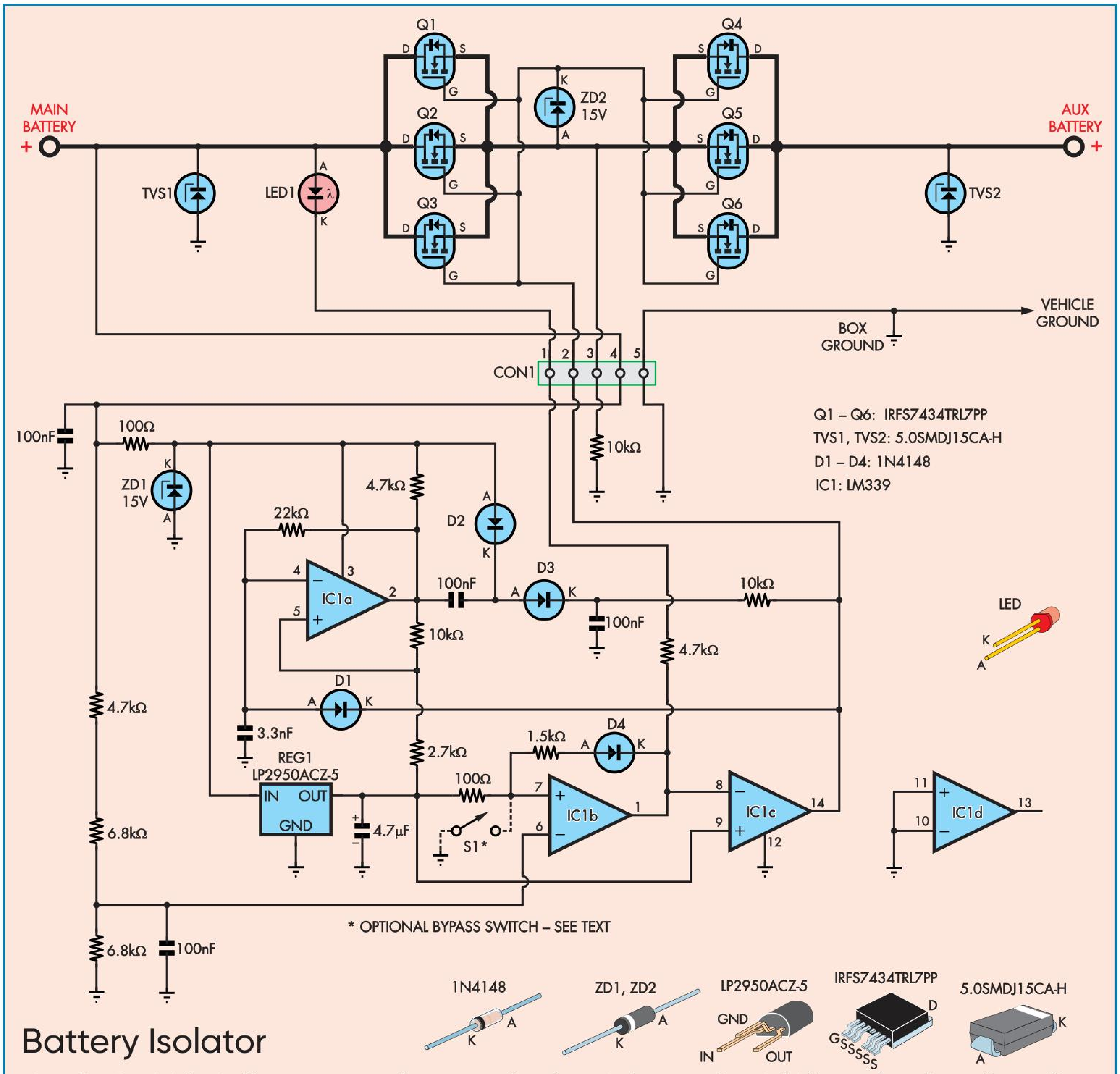

Q1
Q2
Q3
Q4
Q5
Q6
D
S
G
ZD2
15V
K
A
MAIN BATTERY
+
AUX BATTERY
+
TVS1
LED1
TVS2
VEHICLE GROUND
BOX GROUND
1 2 3 4 5
CON1
Q1 – Q6: IRFS7434TRL7PP
TVS1, TVS2: 5.0SMDJ15CA-H
D1 – D4: 1N4148
IC1: LM339
100nF
100Ω
ZD1
15V
4.7kΩ
22kΩ
D2
10kΩ
IC1a
100nF
D3
100nF
10kΩ
4.7kΩ
D1
4.7kΩ
3.3nF
2.7kΩ
REG1
LP2950ACZ-5
IN
OUT
GND
4.7µF
100Ω
1.5kΩ
D4
IC1b
S1*
IC1c
IC1d
6.8kΩ
6.8kΩ
100nF
LED
* OPTIONAL BYPASS SWITCH – SEE TEXT
1N4148
ZD1, ZD2
LP2950ACZ-5
IRFS7434TRL7PP
5.0SMDJ15CA-H
Battery Isolator

Fig.1: the circuit is basically a comparator that senses when the main battery voltage is high enough to charge the auxiliary battery and turns MOSFETs 1-6 (or 1-12) on to do so. When the main battery voltage drops the MOSFETs turn off.

rent flowing through that 10kΩ resistor to ground, holding the gates low.

At the same time, to save power, when pin 14 goes low, diode D1 becomes forward-biased and this discharges the 3.3nF timing capacitor, disabling the oscillator which generates the gate drive voltage. Zener diode ZD1 protects IC1 from supply spikes, in combination with the 100Ω series resistor from the main battery, which limits the current through ZD1 should it conduct. Zener diode ZD2 protects MOSFETs Q1-Q6 from damage due to excessive gate voltages.

This is important, because when the ~20V gate drive is initially applied, their sources are at 0V, and this could otherwise exceed their maximum ±20V V_{GS} ratings. However, ZD2 will not conduct for long, as the source voltage will quickly rise, reducing V_{GS} to around 7-8V under steady-state conditions.

TVS1 and TVS2 are transient voltage suppressors, similar to zener diodes but more robust. These protect the unit and especially the MOSFETs from high-voltage transients which are common in the automotive environment.

Construction

The prototype was built on two boards, with the control circuitry on a piece of stripboard and the MOSFETs, TVSs and battery connectors soldered to a double-sided ‘blank’ PCB which was manually cut into large, isolated sections of copper that the components were then soldered to.

You can also build it this way, and we will give some information later on how to do so. However, to make your life easier, we have produced two commercial double-sided PCB designs. Again, one is for the control circuitry and the other for the larger components. You then just need to solder the components to these two boards, join them and mount them in the case.

Fig.2 shows the control board, while Fig.3 is the MOSFET board overlay diagram. Use these and their matching photos as a guide during construction.

While the prototype had all six MOSFETs on the same side of the board, our MOSFET PCB (see Fig.3a) actually has twelve possible MOSFET-mounting locations; six on the top and six on the bottom, with each pair of MOSFETs directly above and below each other (Q1 and Q1’, Q2 and Q2’...).

Fig.3b shows where the MOSFETs can be mounted on the underside of the board.

This gives you the option to mount three or four MOSFETs on one side of the board and the remainder on the other side, which will help to more evenly distribute what little heat is generated in the device, and may also make slightly better use of the copper, reducing losses a little. But it's a minor advantage, and you could just as easily fit them all one side, which is what we did.

For the control board, install the resistors where shown, then the 1N4148 diodes, ensuring that in each case, the cathode stripe is oriented as indicated.

You can then fit the single zener diode, with its cathode stripe facing to the left. Next, solder IC1 to the board, ensuring that its pin 1 dot/notch faces towards the top as shown. We don't recommend that you use a socket because these can cause failures over time.

Now fit the non-polarised capacitors, which can be either ceramic or MKT types, followed by the single electrolytic capacitor, with its longer positive lead through the right-hand pad (marked with a '+' symbol).

That leaves REG1 and CON1. Gently bend REG1's leads to fit the PCB pads, then solder it in place. CON1 is a regular 5-pin header that's soldered to the top side of the board. You can then move on to the MOSFET board.

Building the MOSFET board

This board has eight SMDs (six MOSFETs and two TVS diodes) plus three through-hole components, not including the battery connections, which we'll explain below.

Start by soldering the MOSFETs. These are quite large and are soldered to large, thick copper planes, so you will need a hot iron to solder them.

In each case, start by spreading a thin layer of flux paste over all the pads, especially the large one for the tab. Then position the MOSFET and solder its pin 1 (near the dot). This is the gate connection so should be the easiest to solder.

Check that all the pins and the tab are lined up correctly. If not, re-heat that solder joint and nudge the device slightly. Solder the remaining five small pins next. It doesn't matter if you accidentally bridge them to each other, as long as they don't bridge to the middle stub pin (which is not connected on this board) or pin 1 (the gate drive).

Finally, flow solder onto the junction of the tab and its large mounting pad underneath. You will need to apply heat and feed in solder until the solder flows to form a smooth fillet between the two. It's OK to add a little extra solder until it covers the tab. The flux you added earlier should aid in this process.

Repeat the above for the other five MOSFETs. Then solder the two TVS diodes in place using a similar procedure; ie, applying flux paste to both pads, tacking the part down on one side, soldering the other side, then refreshing the first solder joint to ensure it is reliable.

Next, solder ZD2 and LED1 in place on the top side, with the orientations shown. It's a good idea to fit LED1 with some space between its lens and the PCB, so that it can poke through a hole in the case. The base of its lens should be a little bit more than the thickness of one M8 nut above the board.

Having done that, fit 5-pin header socket CON2 on the underside of the board. The easiest way to do this is to plug CON2 into CON1 on the control board, attach the two boards using the four corner mounting holes, 12mm tapped spacers and short machine screws, and then solder CON2 to the MOSFET board. That ensures the two headers line up properly.

The M8 brass screws that will be used as the battery terminals can now be fed through the MOSFET PCB, with a shakeproof or crinkle washer under the screw head (which goes on the bottom side of the board) and another under the nut which is done up tightly on the top side of the board.

This should give good electrical contact to the PCB and means that you don't need to solder the screws and nuts to the boards, which is difficult and makes disassembly impossible. (You can see that this was done on the prototype in the photos below.)

While the MOSFET board is now complete, you could consider adding some tinned copper wires in parallel with the copper on the board. This will reduce the voltage drop across the device, as well as its dissipation, and make it more robust. However, we do not feel that this is strictly necessary due to the use of extra-thick 2oz copper on this board.

If you do want to run some extra wire, you can solder lengths of tinned copper wire from between pins 2 and 3 of each MOSFET to between pins 5 and 6 on the MOSFET on the other side of the board. You can then solder wires from the tabs of each MOSFET to the nearby battery terminal.

You may be able to solder these to the exposed copper around the nuts, or directly to the nuts themselves, with a very hot iron.

Make sure any added wires do not project above the board any higher than the bodies of the MOSFETs; otherwise, they could potentially short to the metal lid of the case.

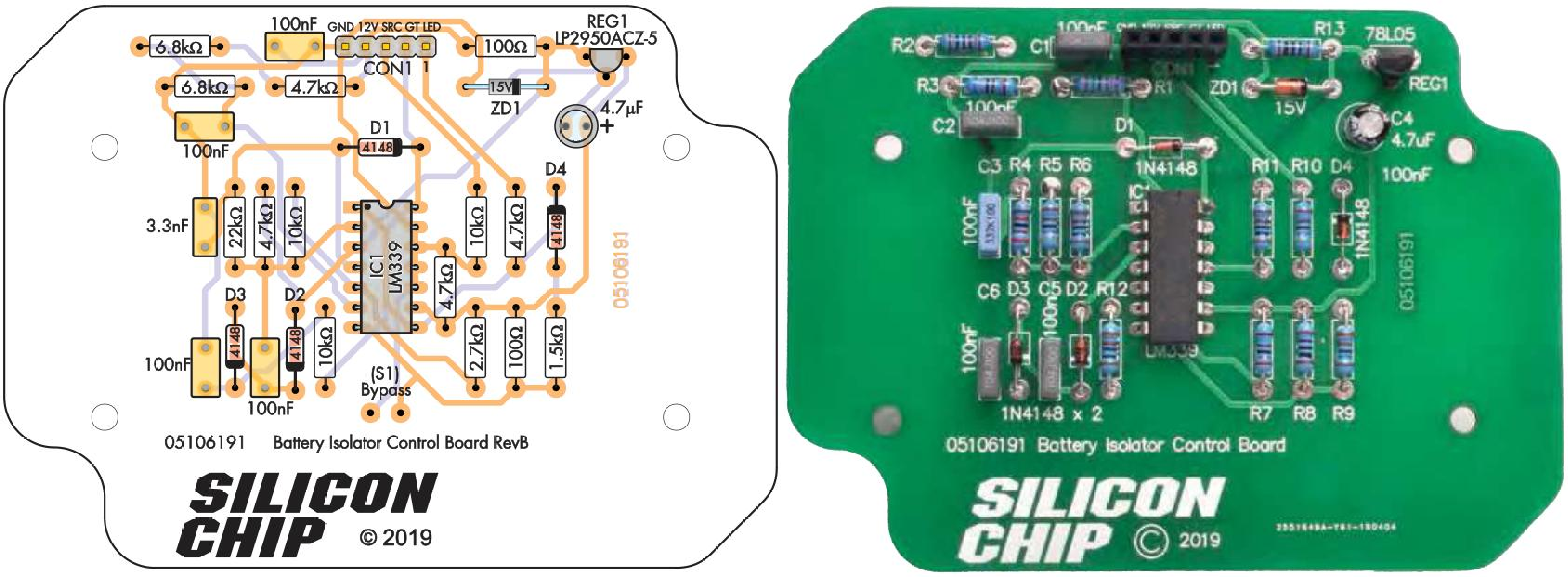
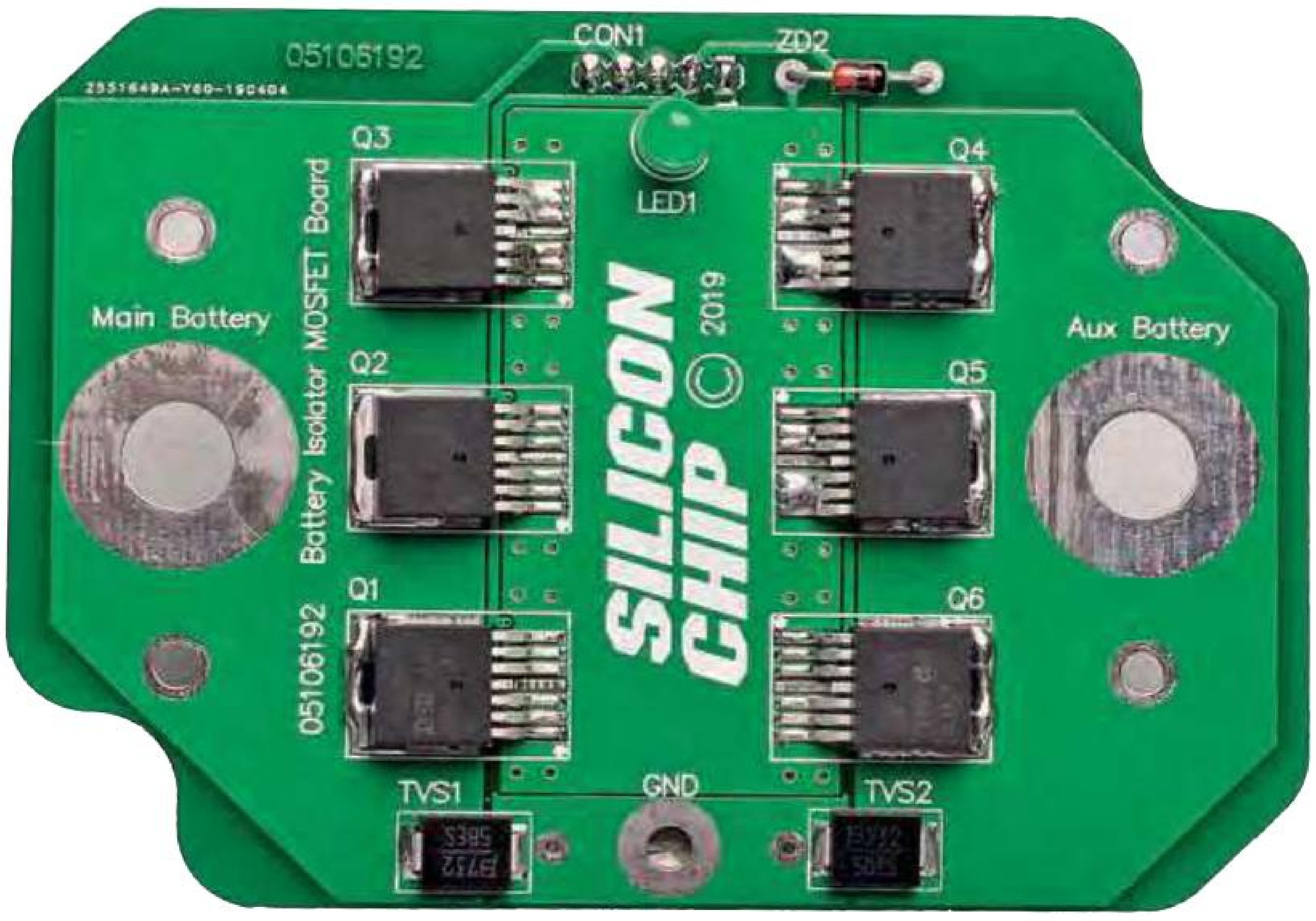
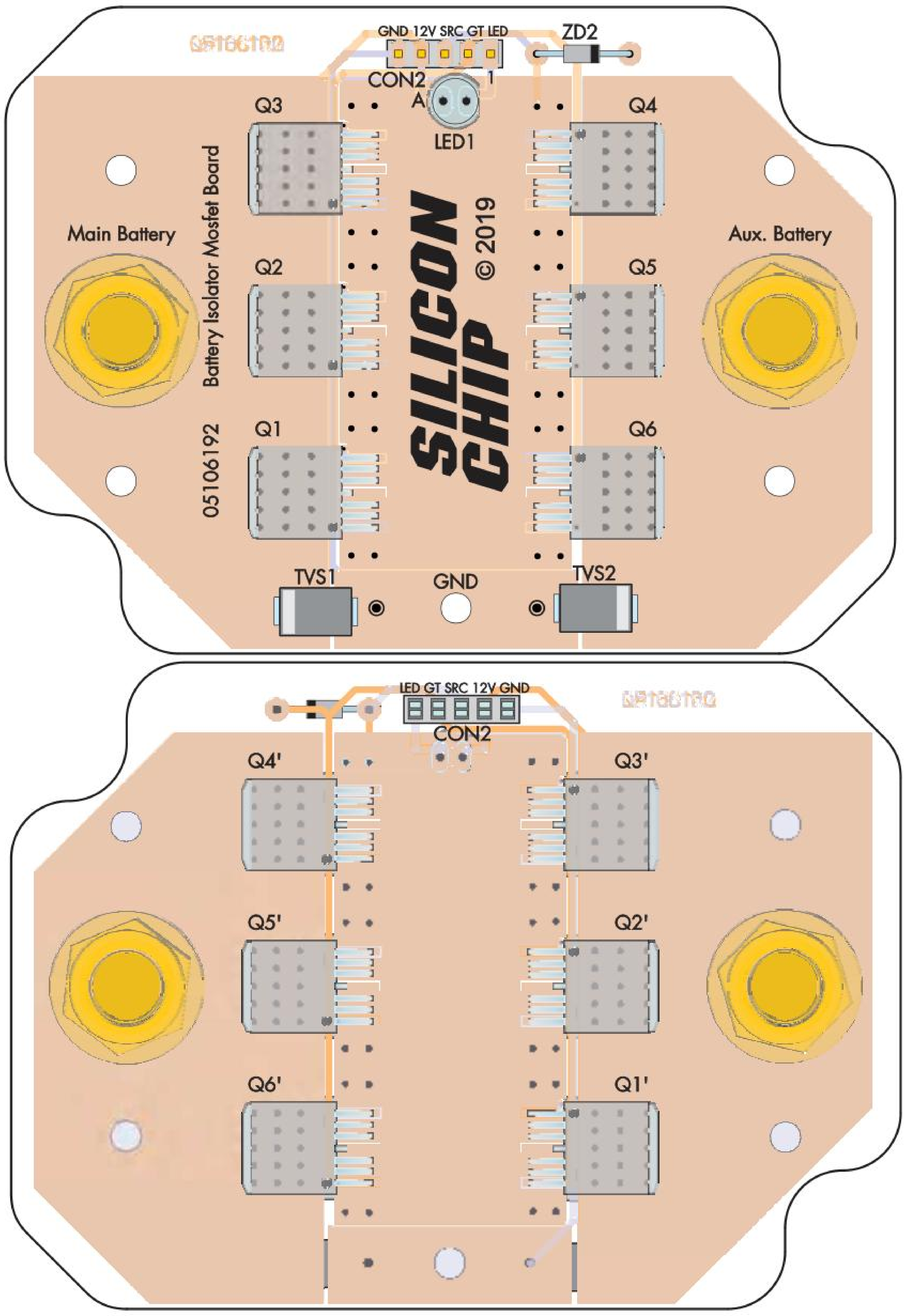


Fig.2: one of two PCBs in this project, the control board, with matching photo alongside. You could also build this on stripboard if you wished (see end of article) but PCBs make a much neater job and minimise the chance of errors. (Note that we fixed an error with a missing resistor on the board, so the photo doesn't quite 'match' – the diagram is correct.)


05106192
CON1
ZD2
Q3
Q4
LED1
Main Battery
Aux Battery
Battery Isolator MOSFET Board
SILICON CHIP
© 2019
Q2
Q5
Q1
Q6
05106192
TVS1
GND
TVS2

Here's the top side of the completed MOSFET PCB. It's fitted with six MOSFETs as shown in Fig.3a (top). But if you wish, another six MOSFETs can be soldered to the underside of the PCB for even better current handling (Fig.3b, lower)


GND 12V SRC GT LED
ZD2
CON2
A
1
Q3
Q4
LED1
Main Battery
Aux. Battery
Battery Isolator Mosfet Board
SILICON CHIP
© 2019
Q2
Q5
Q1
Q6
05106192
TVS1
GND
TVS2
LED GT SRC 12V GND
CON2
Q4'
Q3'
Q5'
Q2'
Q6'
Q1'

Testing

Ideally, you should use an adjustable bench supply with current limiting for testing. Set it to 12V and around 50mA, then apply power between the main battery terminal and the ground pad on the MOSFET PCB (or pin 5 of CON1 or CON2). You should observe a current flow which settles at around 8mA. LED1 should remain off.

Measure the voltage at the auxiliary battery terminal relative to GND. It should be low, close to 0V. Now increase the supply to around 14V.

You should observe LED1 switch on. The current draw should increase slightly. The voltage at the auxiliary battery terminal should now have risen to the supply voltage.

Reduce the supply voltage back to 12V and confirm that LED1 switches off and the voltage at the auxiliary battery terminal drops back to 0V within a few seconds. This verifies that everything is working as intended and you can now proceed to finish construction.

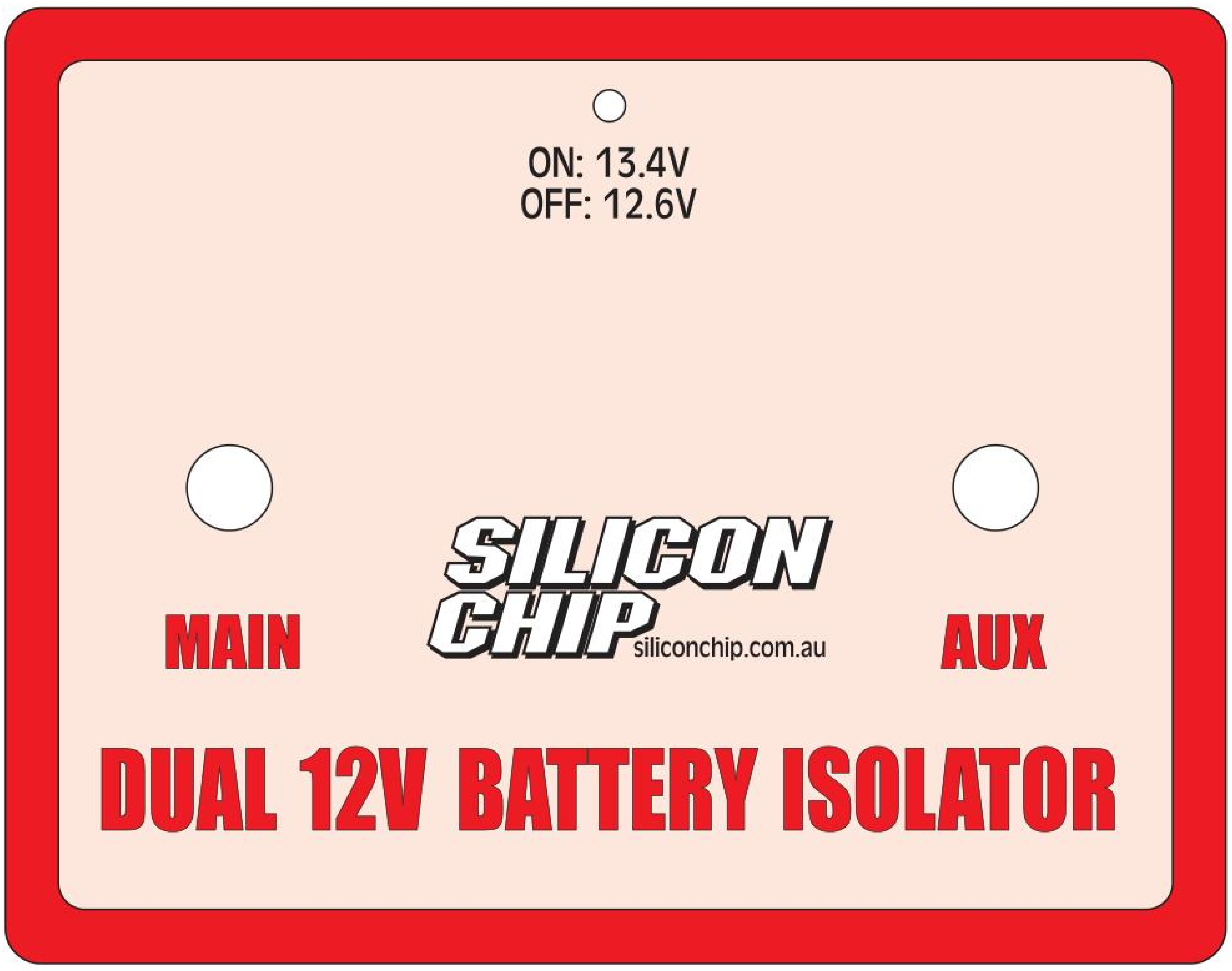
Adding a bypass switch

There may be times where the vehicle battery is low, but you still want to connect it to the auxiliary battery. One example would be if the vehicle battery is flat but the auxiliary battery is charged, and you want to 'jump start' the vehicle using the auxiliary battery.

While you could do this with a screwdriver across the terminals, it's much nicer to have a switch which forces the unit to operate.

This is quite easy to do, but it does have one limitation in that this won't work if the vehicle battery is dead flat, since the unit is powered from it. But it should work down to at least 10V, or possibly even less.

The easiest way to achieve this is to connect a switch between pin 7 of IC1b and GND. When this switch is closed, it will pull that pin down to 0V, which means that the voltage at pin 6 will always be higher than pin 7, so output pin 1 will go low, switching on MOSFETs Q1-Q6. This switch is shown with dotted connections in Fig.1.


ON: 13.4V
OFF: 12.6V
MAIN
SILICON CHIP
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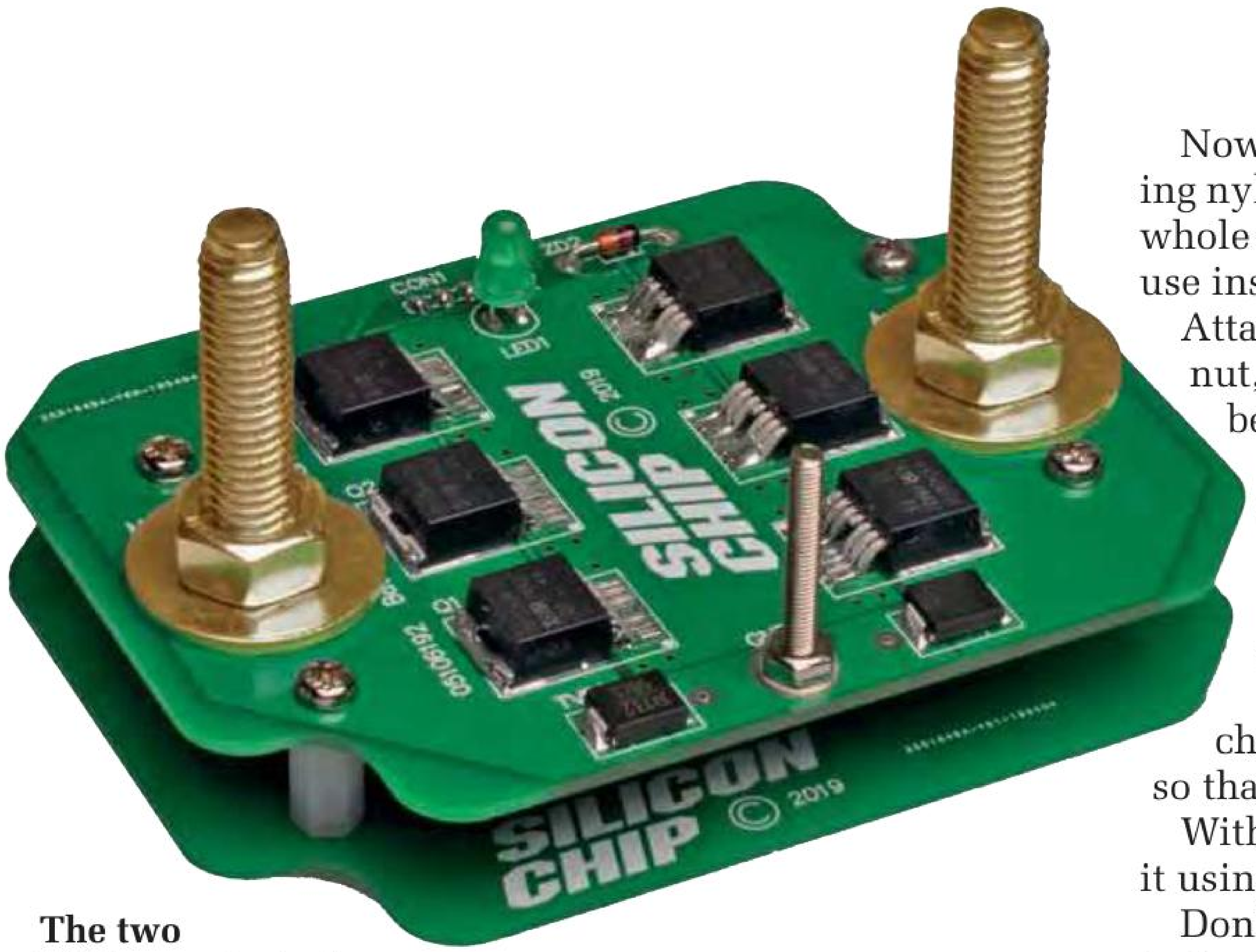
AUX
DUAL 12V BATTERY ISOLATOR

Fig.4: this is the artwork for the *12V Battery Isolator* front panel. It can be downloaded from the July 2020 page of the *PE* website. Ideally, it should be laminated before glueing in place.



The two PCBs are stacked as shown, with the 8mm brass battery connection posts fitted firmly in place with washers ensuring good contact with the PCB tracks.

We've also shown the most convenient points to solder wires to go to the switch in Fig.2 and Fig.3. Simply solder a wire here, to the COM terminal of an SPST switch, then a wire from the NO terminal of that switch to a convenient ground point.

When you activate this switch, you need to remember to switch it back into its normal position later, for the unit to go back to doing its job!

Case assembly

There are only four holes to drill: two in the lid for the battery terminals (main and auxiliary), plus one for the LED, and one 3mm hole in the side of the case for the ground eyelet.

If you're installing the optional bypass switch (S1), then you may wish to mount it on the lid, in which case you will need to drill an extra hole. Make sure that the switch won't foul the MOSFET board once it's mounted.

You will probably find that you have more room if you mount it low on the side of the case, and that may also make it harder to trigger the bypass function accidentally.

If you are using a metal case, the ground is connected to the case internally, and then externally, to the vehicle chassis or one of the battery terminals. You will also need to find a way insulate the two 8mm bolts from the lid of the case.

With a plastic case, the easiest way to provide a GND terminal is to feed a long M3 screw through the GND terminal on the MOSFET board, attaching it to the PCB in a similar manner as the two large 8mm screws (ie, with shakeproof washers and nuts). This can then project up through a fourth hole in the lid.

Or you could connect the ground eyelet to a screw which is externally accessible elsewhere.

There's no need to provide any insulation for the 8mm screws when using a plastic case; however, you will need to seal all the exit holes with neutral cure clear silicone, to ensure that the case remains watertight.

Download the panel label artwork from the July 2020 page of the *PE* website and print it at actual size. You can then cut it out and use it to mark out the hole positions in the lid. Drill them all to 3mm, then enlarge the two battery terminal holes to 8mm with larger drills, a stepped drill bit or a tapered reamer.

Laminate the label and cut out the holes using a sharp hobby knife. You can then stick it to the lid using contact adhesive or a thin smear of neutral-cure silicone.

Now plug the two boards together and join them using nylon tapped spacers and machine screws. Mount the whole assembly on the underside of the lid, remembering to use insulators for the 8mm screw shafts if the lid is metal.

Attach the assembly to the lid using a flat washer and nut, then another flat washer and nut, which can later be used to clamp the battery wires or terminals.

Seal any possible water entry points (eg, around the LED lens) with neutral-cure silicone, then, if using a metal case, drill a hole in the side of the case for the ground eyelet and attach it using a machine screw, shakeproof washer and two nuts.

You can then insert the sealing gasket into the channel in the underside of the lid, cutting it to size so that it fits around the full circumference.

With that in place, lower the lid onto the case and attach it using the supplied screws.

Don't forget to attach the case (if metal) or ground screw to the vehicle's ground, either via the chassis or to one of the battery negative terminals.

Parts list – Solid-state Dual Battery Isolator

1 double-sided PCB coded 05106191, 98 x 71mm
1 double-sided PCB **with 2oz copper**, coded 05106192, 98 x 71mm – both PCBs available from the PE PCB Service
1 IP65 diecast aluminium box, 115 x 90 x 55mm [Jaycar HB5042/HB5044, Altronics H0423] ***OR***
1 IP65 polycarbonate box, 115 x 90 x 55mm [Jaycar HB6216/HB6217]
1 panel label, 115 x 90mm
2 35mm long M8 brass screws – available from ship's chandlers and speciality fastener shops
6 M8 brass hex nuts
6 8mm ID brass flat washers
4 8mm ID brass or beryllium copper star/crinkle washers
4 8mm ID nylon screw insulators (if using a metal case)
4 12mm long M3 tapped nylon spacers
8 M3 x 6mm panhead machine screws
2 small eyelet quick connectors
1 M3 x 10mm panhead machine screw, shakeproof washer and two hex nuts

Semiconductors
1 LM339 quad comparator, DIP-14 (IC1)
1 LP2950ACZ-5.0 5V low-dropout linear regulator, TO-92 (REG1)
6 40V 100A+ N-channel MOSFETs, TO-263-7 (Q1-Q6) [eg Infineon IRFS7434TRL7PP*]
1 5mm LED (LED1)
2 15V 1W zener diodes (ZD1,ZD2)
2 5kW 15-18V transient voltage suppressors, DO-214AB/SMC (TVS1,TVS2) [eg, Bourns 5.0SMDJ15CA-H*]
4 1N4148 small signal diodes (D1-D4)
1 5-pin SIL socket (CON1)
1 5-pin header (CON2)

** available from Mouser or Digi-Key*

Capacitors
1 4.7µF 50V electrolytic
4 100nF 50V ceramic or MKT
1 3.3nF 50V ceramic or MKT

Resistors (all 1/4W 1% metal film)
1 22kΩ 3 10kΩ 2 6.8kΩ# 3 4.7kΩ#
1 2.7kΩ 1 1.5kΩ 2 100Ω
# use ±0.1% tolerance resistors for the tighter threshold ranges mentioned in the text

You can then wire up the two battery positive wires to the unit and verify that LED1 lights and the auxiliary battery begins to charge when you switch on the engine.

Don't forget to use heavy automotive cable with a sufficiently high current rating (25A+) to handle the high charging currents which can occur. The prototype used 35mm^2 automotive starter motor cable.

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Alternative construction method using stripboard and hand-cut PCBs

Instead of using the PCBs that we designed, you could copy the approach used for the prototype and build the control system on a piece of stripboard (Veroboard, for example) and handmake your own PCB to host the MOSFETs and related components.

My suggested stripboard layout is shown at right. This requires a board with at least 13 strips and 21 rows of holes. The diagram is drawn looking from the top of the board (ie, from the non-copper side). The copper tracks are shown as a visual aid, as if you can see them through the board.

You may want to use a larger piece of stripboard so that you have space to drill some mounting holes later. Before fitting the components, cut the tracks in the sixteen locations shown (including all seven tracks under IC1). It's often easier to cut the tracks with a 3mm twist drill, just removing the copper around the hole. After soldering the components in place, fit the wire links.

The shorter links can be made using component lead off-cuts, or in some cases, by merely bridging adjacent tracks with solder. Longer links are best made with solid-core insulated wire (eg, Bell wire).

For the MOSFET board, you will need a piece of double-sided copper laminate around 100 x 100mm (slightly smaller, if you're planning to fit it into the specified box; check it fits before proceeding). Ideally, this should have thicker-than-normal copper (eg, '2oz', which is double normal PCB copper thickness).

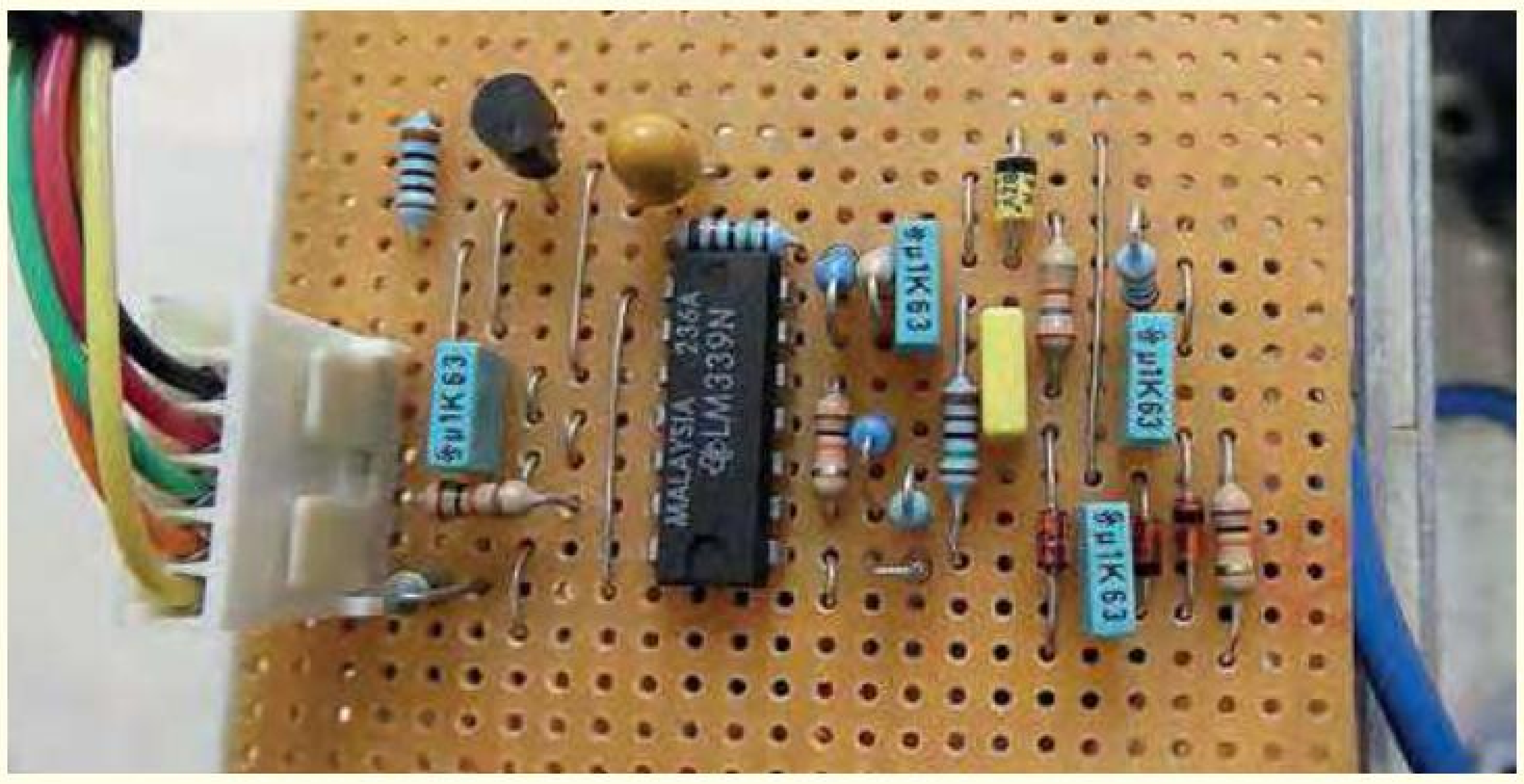
The required layout is shown clearly in the photos below. On the top of the board, you will need to make three straight cuts (eg, using a rotary cutting disc) to separate the copper into four islands.

The central islands should be around 25mm wide. Be careful not to cut through the fibreglass substrate; just the copper. Ensure the cuts are wide enough to guarantee electrical isolation. The underside requires just one cut down the middle, separating the copper on either side.

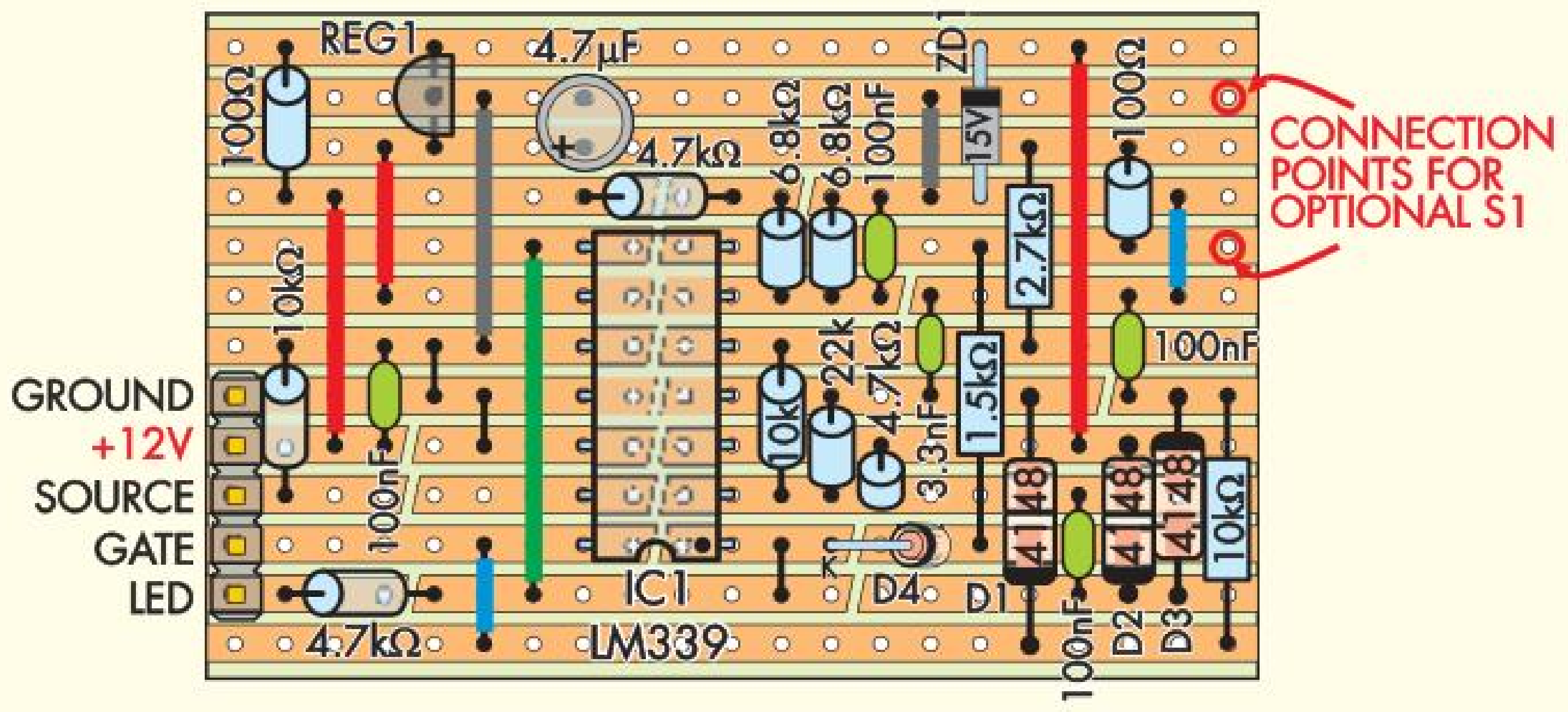
Next, drill two 8mm holes for the battery terminals and eight 2mm diameter holes (around the locations where the MOSFET tabs will be soldered) for wire vias to pass through later. Now is also a good time to drill four 3mm holes which the control board will be mounted to later (lining up with holes on that board).

Bend pin 1 (the gate) of each MOSFET up, then solder the remaining five small pins to the central island. Be careful to place the MOSFET so that the body does not bridge the cut in the copper plane. Then, using a hot iron, solder the tabs in place. Join the gates with light-duty wire; it's easier to use stiff bell wire, but you could use Kynar or multi-strand wire.

The small copper island at the bottom is the ground connection point. Solder the anodes of the two TVSs to this island, with the cathodes to the large planes on either side. You can now add the zener diode, with its anode to the large central copper area and its cathode to the MOSFET gate wire.



Stripboard prototype with matching layout below. Don't forget to cut the tracks where indicated – you'll have a massive short circuit otherwise!



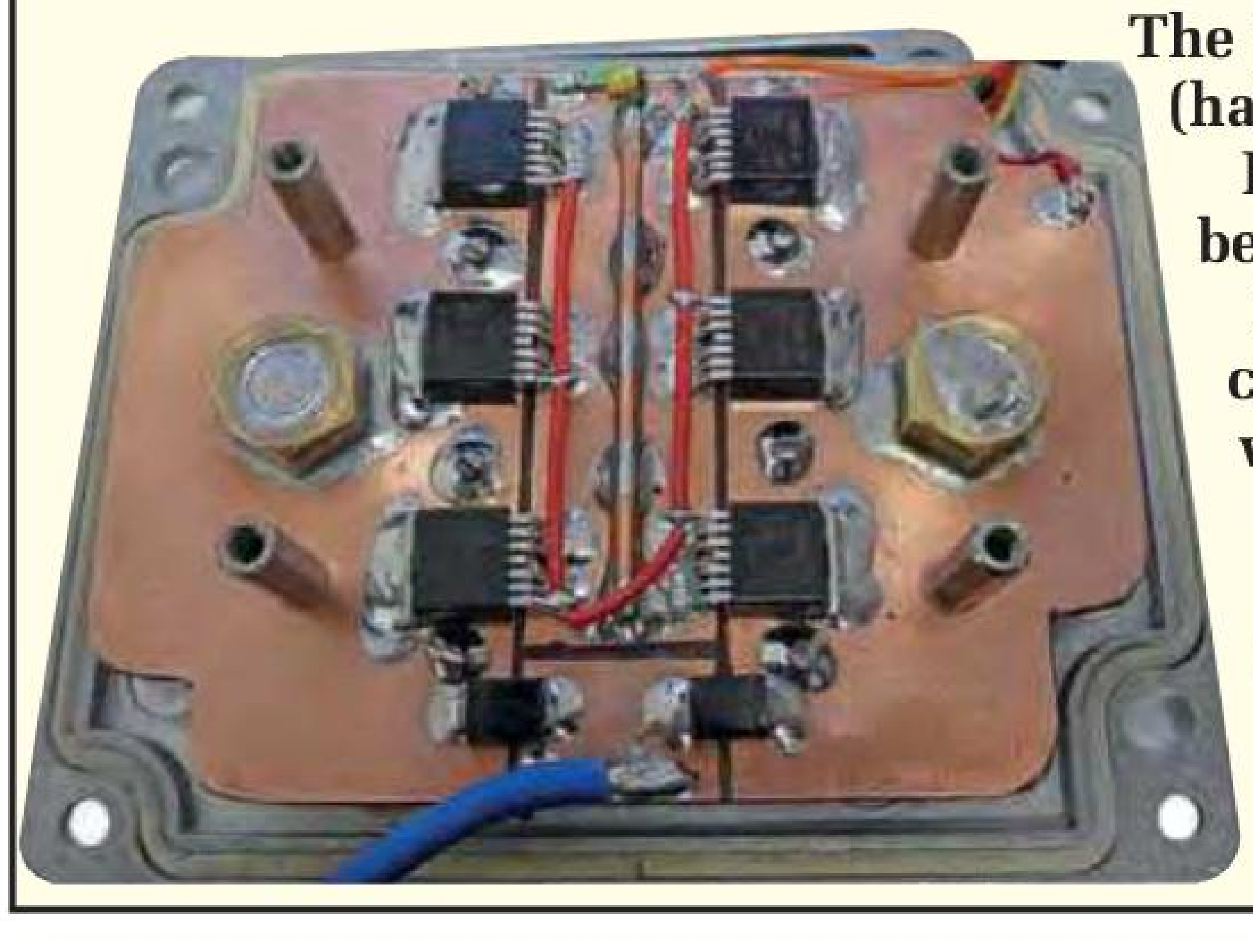
Next, run a strip of thick copper wire down the central island, soldered near every pair of MOSFETs, plus wires on the underside fed through each of the 2mm holes you drilled earlier and bent over to touch the battery terminals. Solder them near the terminals and on both sides of the 2mm holes to form vias.

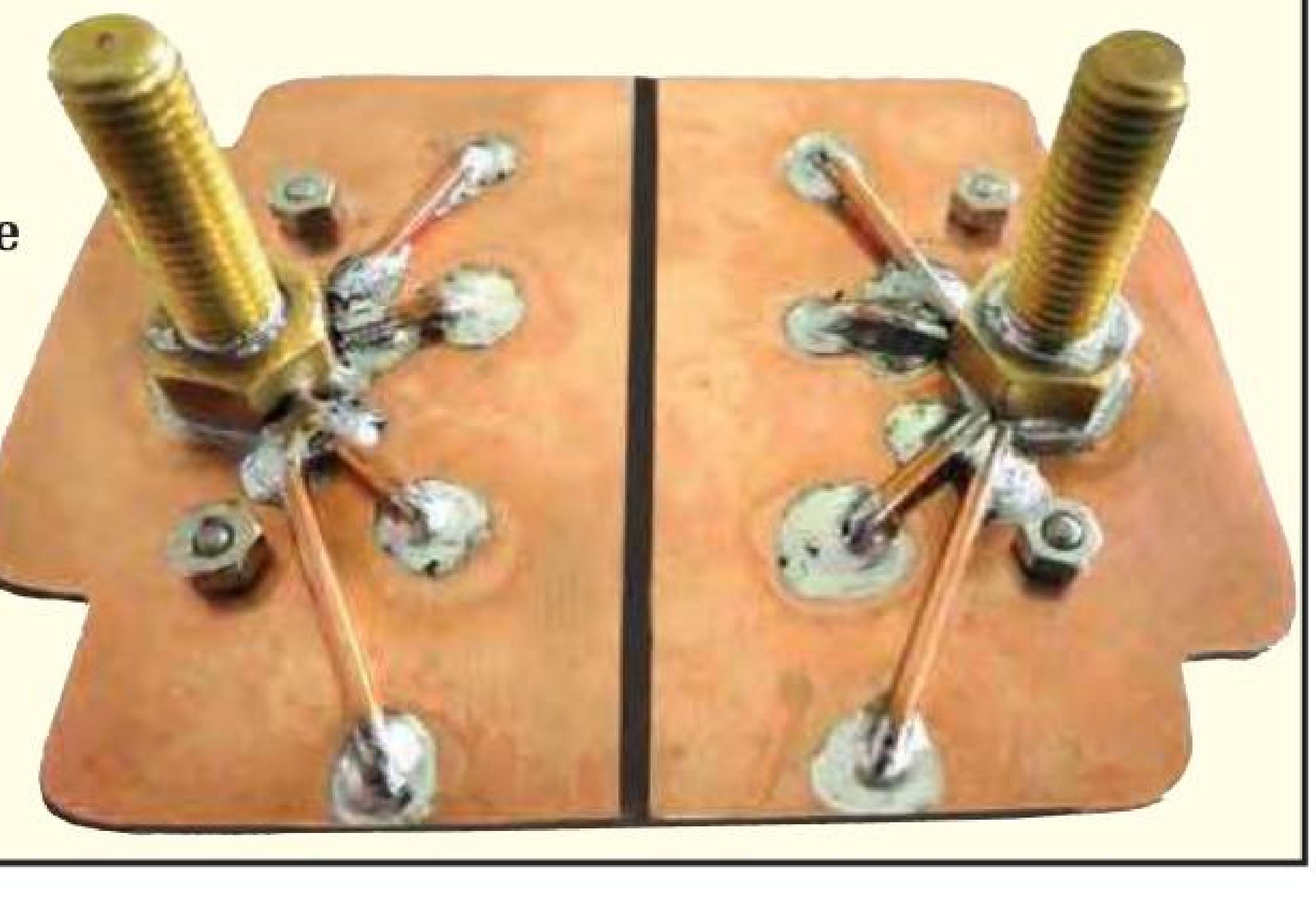
If you can't easily get thick copper wire, you can use a bundle with multiple pieces of 0.71mm- or 1mm-diameter tinned copper wire.

Solder four wires to this PCB: one to the main battery terminal side, to supply 12V to the control board; one to the small ground area, to connect to GND on the control board; one to the cathode of the zener diode, which goes to the gate drive pin on the control board; and one to the central copper island (or zener diode anode), which goes to the control board MOSFET source terminal.

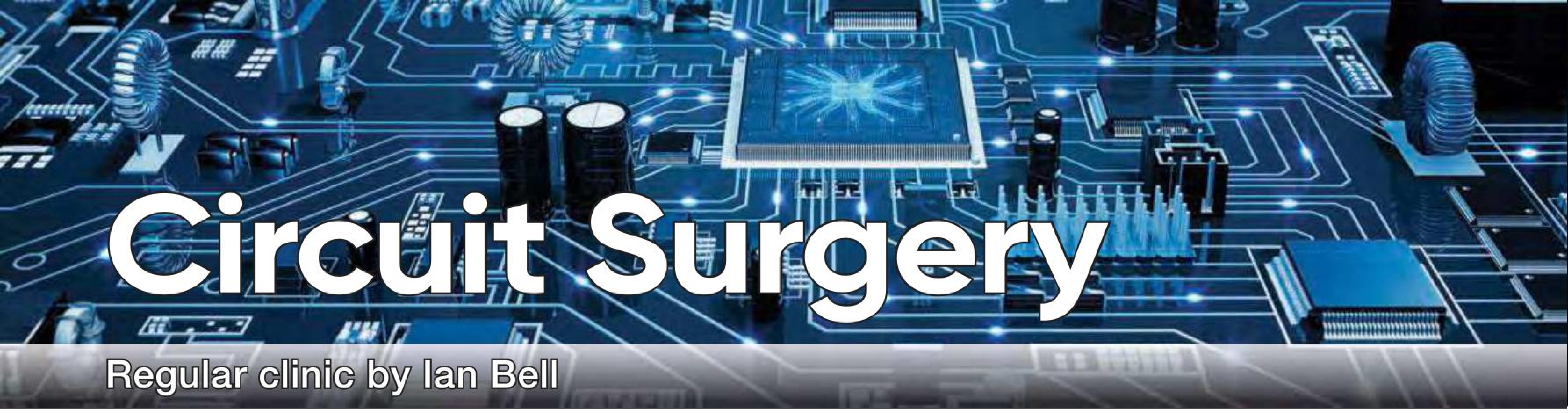
Note, though, this source terminal only connects to a 10kΩ resistor with the other end connected to GND. So you could make your life slightly easier by simply soldering a 10kΩ resistor between the two central copper islands on the MOSFET board and then you won't have to run this fourth wire.

The only part that's left now is LED1, which can be chassis-mounted to your box, with its anode connected to pin 4 of CON1 on the control board, and its cathode to pin 1. Make the three other connections from your MOSFET board to CON1 on the control board, as described above, and you are ready for testing.





The photo at left shows the original (hand-made) prototype 'MOSFET PCB' with its hand-cut breaks between the copper sections. Note how the gate pins here are all connected to (the red) insulated wire, not to the PCB.At right is the opposite side, with 8mm brass bolts soldered firmly in place, with heavy copper wires which pass through the board and which are soldered to the top copper as well.



Circuit Surgery

Regular clinic by Ian Bell

LTspice sources and waveform import/export

In last month's article on class D, G and H amplifiers we made use of behavioural sources in the LTspice circuit simulator to draw waveforms to illustrate the article. There was insufficient space to explain much about this aspect of LTspice, so now we are going to take a more in-depth look at LTspice sources in general. Also, I was recently asked by someone about how you can get data in and out of LTspice for use with other applications. This is related to the uses of sources in creating and manipulating complex waveforms, so we will look at that too, including importing and exporting WAV audio files as these provide the opportunity to have some fun listening to the results of your circuit simulations.

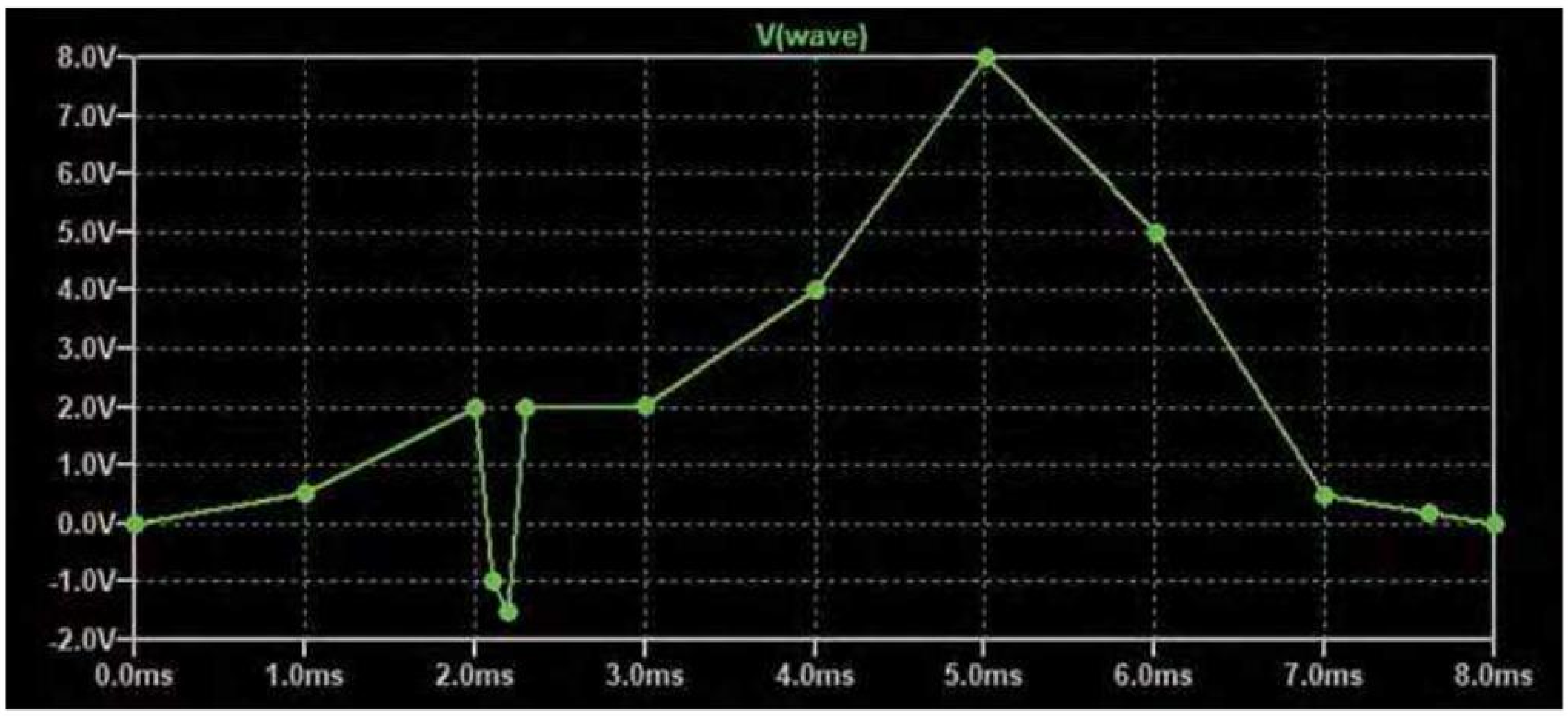
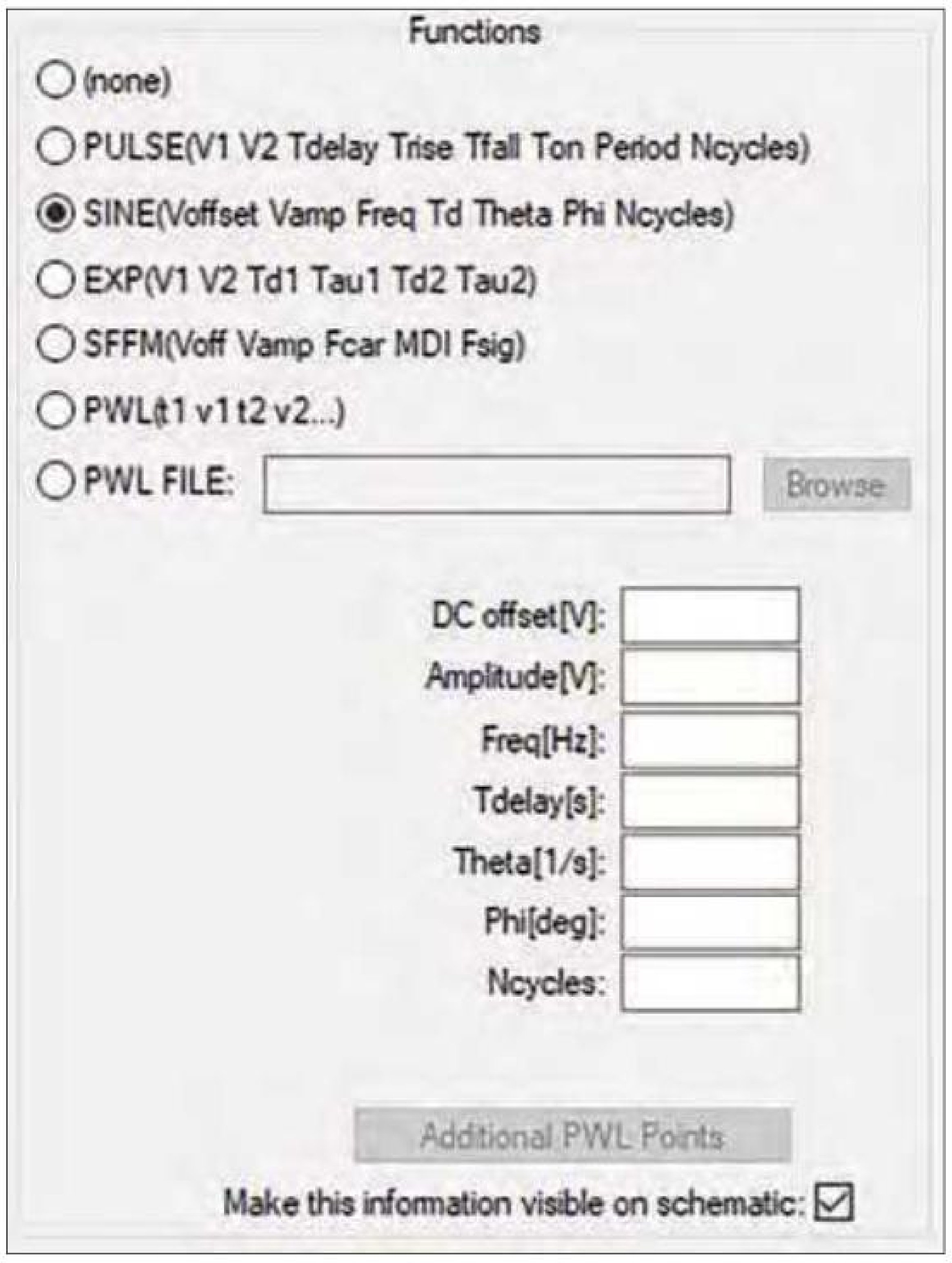


Fig.2. Example arbitrary PWL waveform imported from a text file (for file contents see text).

Sources

In SPICE, and electronics in general, a source is something which outputs voltage or current, which, depending on the context of its use, will be regarded as a signal, a reference level or a power supply. The output from a source may be anything from a constant (DC) value (typical for references and power supplies) through basic AC signals, such pulses and sinewaves, to highly complex waveforms such as audio. In LTspice (and SPICE in general) there are a variety of components that can be added to a circuit to act as sources. The most basic of these are simply called `Voltage` and `Current`. The names of components in SPICE start with a letter indicating the type of component – for these basic sources it is `V` and `I`.



Functions

○ (none)

○ PULSE(V1 V2 Tdelay Trise Tfall Ton Period Ncycles)

● SINE(Voffset Vamp Freq Td Theta Phi Ncycles)

○ EXP(V1 V2 Td1 Tau1 Td2 Tau2)

○ SFFM(Voff Vamp Fcar MDI Fsig)

○ PWL(t1 v1 t2 v2...)

○ PWL FILE:

DC offset[V]:

Amplitude[V]:

Freq[Hz]:

Tdelay[s]:

Theta[1/s]:

Phi[deg]:

Ncycles:

Make this information visible on schematic: ☑

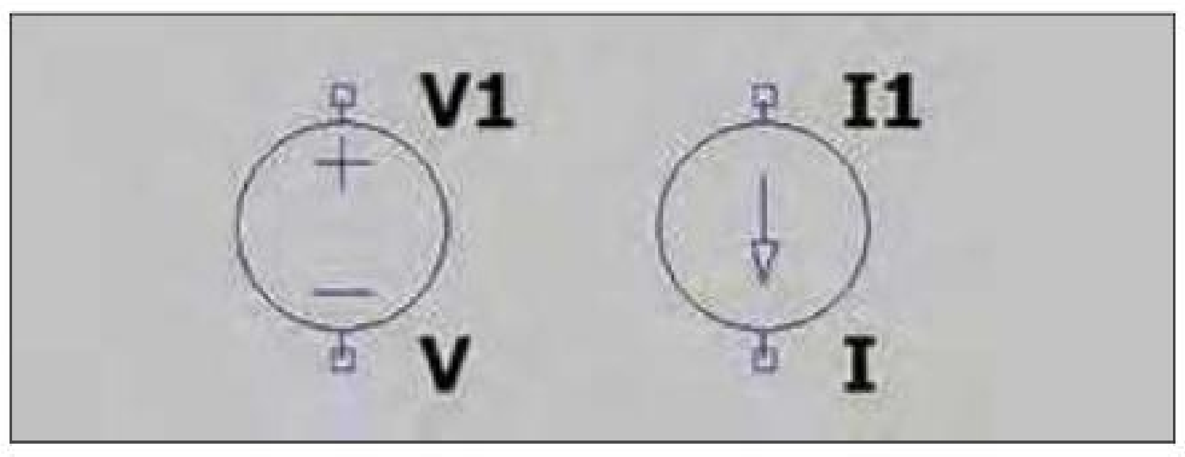


Fig.1. (right) LTspice symbols for independent voltage and current sources and (above) part of the source configuration dialog showing parameters for a sinewave source.

The `V` and `I` sources can be configured to produce a variety of outputs via a dialog. Once the component is placed on the schematic (see Fig.1 below) right-clicking it allows a DC value to be set, but clicking the Advanced button opens another dialog (see Fig.1 left) which allows a variety of signals to be set up. Specifically, these are DC (none), pulses (`PULSE`), sinewave (`SINE`), exponential (`EXP`), frequency-modulated sinewave (`SFFM`) and arbitrary piece-wise linear (`PWL`). Selecting one of these options provides access to dialog inputs to configure the sources as required (for example, the frequency of a sinewave), see Fig.1.

The `PWL` option allows you to define an arbitrary waveform by entering a set of value pairs (a time and the voltage at that time). The main source dialog provides just four points, but you can open another dialog to add more. For more than just a few data points it is often better to use a file for the data (`PWL FILE` option).

The `PWL` file must be a text file containing the list of time and value pairs (one per line) in a tab or comma-delimited format. Unlike some similar data files there must not be any header information, such as a first line with the column headings. You can create the file with a text editor, or use a spreadsheet such as Excel or LibreOffice Calc and work with CSV (comma-separated values) files.

Fig.2 shows an example of a waveform produced from the following text file using the schematic in Fig.3.

```
0,        0
0.001,    0.5
0.002,    2
0.0021,   -1
0.0022,   -1.5
0.0023,   2
0.003,    2
0.004,    4
0.005,    8
0.006,    5
0.007,    0.5
0.008,    0
```

The data points in the waveform are those created by the simulation – not the original input data. Here, they are similar, but simulation has an additional data

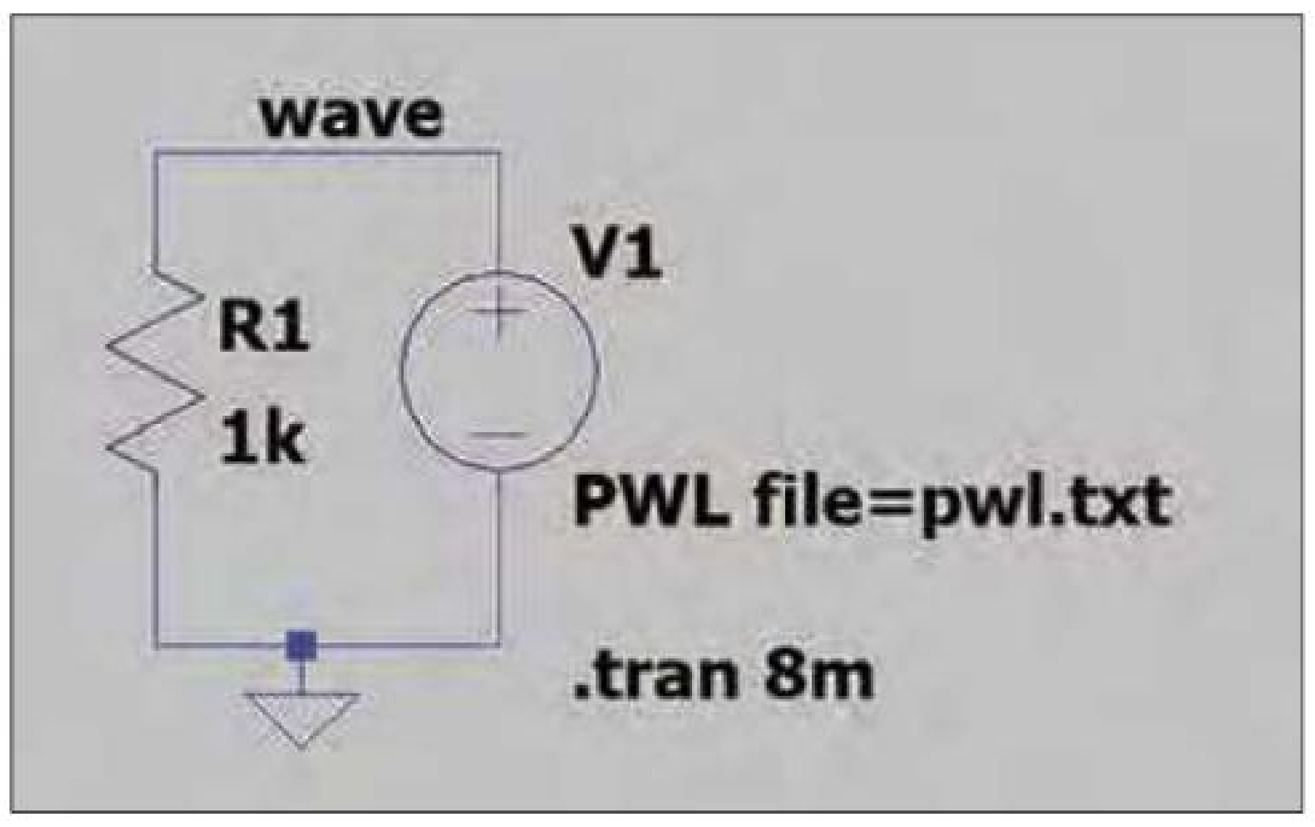


Fig.3. LTspice schematic used to check import of the PWL waveform file in Fig.2.

```
time                     V(wave)          I(R1)
0.000000000000000e+000   0.000000e+000    0.000000e+000
1.000781250000000e-003   5.011719e-001    5.011719e-004
2.000000000000000e-003   2.000000e+000    2.000000e-003
2.100000000000000e-003   -1.000000e+000   -1.000000e-003
2.200000000000000e-003   -1.500000e+000   -1.500000e-003
2.300000000000000e-003   2.000000e+000    2.000000e-003
3.002343750000000e-003   2.004688e+000    2.004687e-003
```

Data exported from the circuit in Fig.3.

point at 6.5ms. In this case the file was in the same folder as the LTspice schematic file, so no path is included with the file; however, the full path can be specified.

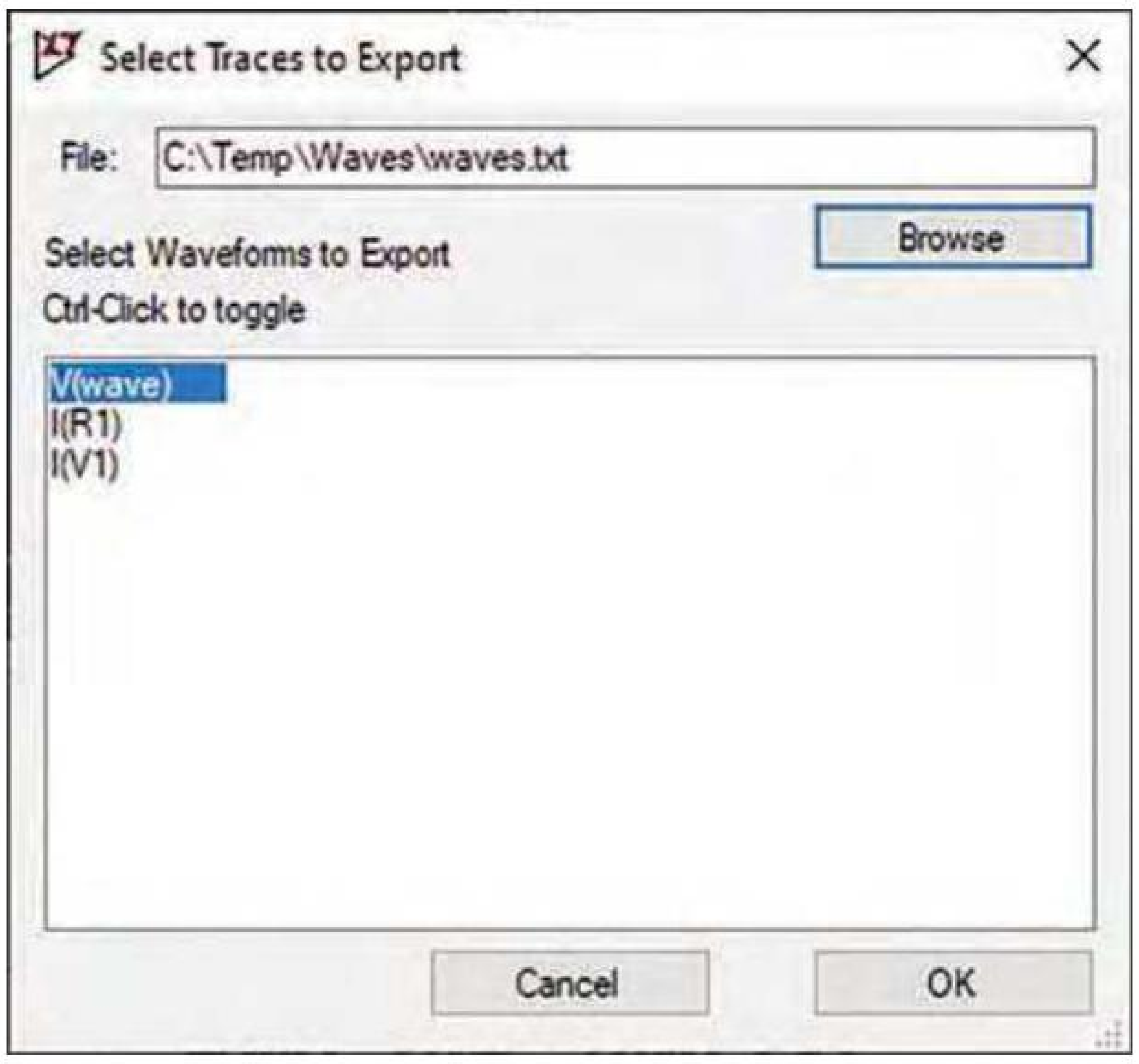
If you are familiar with using formulae in spreadsheet applications, there is potential to use these to create waveforms that are not available from the basic sources settings. If you are a coder then you can write software to generate PWL waveforms and write the data to a text file. Mathematical applications such as MATLAB can also be used to write data out in CSV format that can be read as PWL waveforms in LTspice.

LTspice can also export waveform data to a text file. This is done using the main menu: File > Export data as text with waveform window selected. This opens a dialog which allows you to select the currents and voltages you want into include in the file – for example, see Fig.4 which shows the voltage `V(wave)` and the current in `R1 (I(R1))` from the circuit in Fig.3 selected for export. Part of the resulting file is shown above-right.

The files exported by LTspice are tab separated and include a header row with the column (field) names. The first value on each row is the time, which is followed by the other selected values. These files are readily loaded into spreadsheets and mathematical applications like MATLAB.

Controlled (dependent) sources

The `V` and `I` sources we have discussed so far can produce a wide variety of waveforms, but these are entirely controlled 'inside' the source – there is no direct effect on their output from other signals in the circuit, although loading effects may be modelled if a source's internal resistance is defined (this can be done in the source setup dialog). A source controlled by another voltage or current elsewhere in the circuit is a very useful way to model common circuit behaviours. For example, a voltage amplifier is effectively a voltage source controlled by another voltage – its input signal.



File: C:\Temp\Waves\waves.txt

Select Waveforms to Export
Ctrl-Click to toggle

V(wave)
I(R1)
I(V1)

Fig.4. Exporting LTspice waveforms to a text file.

Controlled sources can be used to create simulations of circuits based on their operating principles, characteristics and behaviour, rather than a full component-based design – these are referred to as 'macromodels' or 'behavioural models'. This is useful for trying out ideas without having to develop a full design at component level. It is also used by manufacturers of components such as op amps to publish accurate simulation models of their ICs without revealing full design details. Furthermore, controlled sources are used within SPICE itself to model active devices such as transistors, and they are used in some published models of common components which are not built into SPICE simulators. The most-basic controlled sources are:

`E` Voltage-controlled voltage source
`F` Current-controlled current source
`G` Voltage-controlled current source
`H` Current-controlled voltage source

These sources are also referred to individually as, for example, a 'voltage-dependent voltage source, and collectively as 'linear dependent sources'. The letters `E`, `F`, `G` and `H` are the initial letters of the element names of these components. The circuit symbols are shown in Fig.5. Note the additional connections for the voltage-dependent sources – the voltage across these points is used to control the source's output. The current-dependent sources do not have control inputs – their control can only come from a voltage source in the circuit.

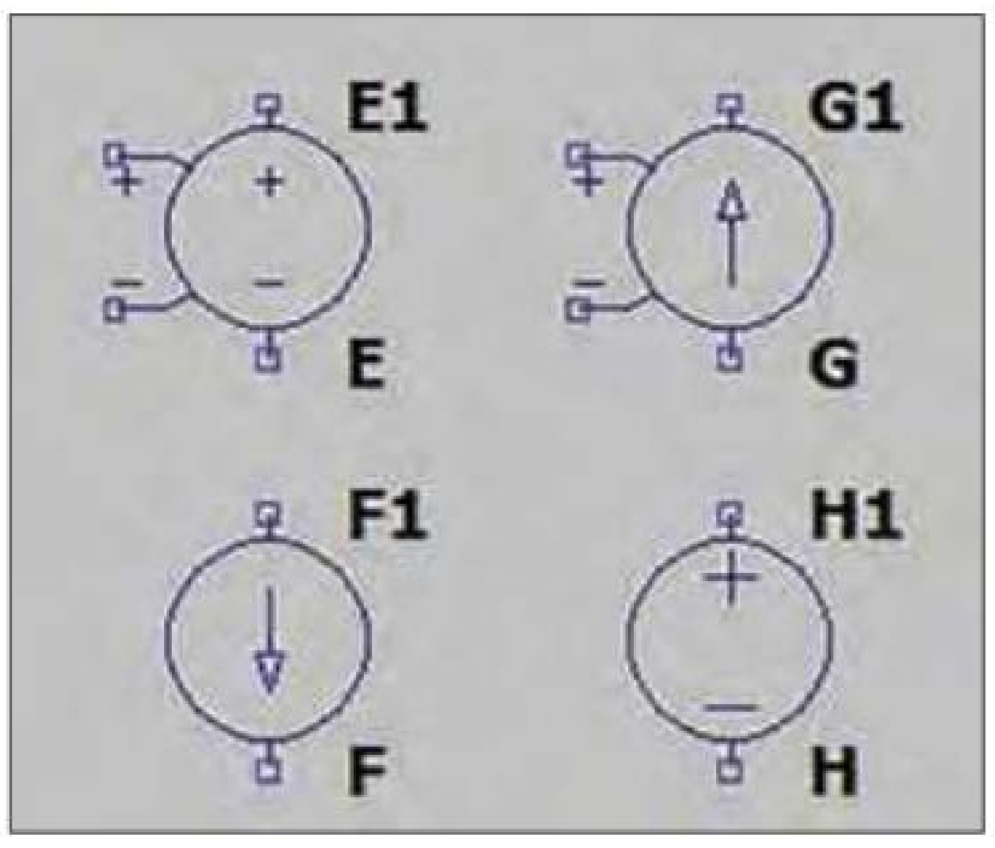


Fig.5. Dependent source symbols.

Transfer Function

To define the behaviour of a controlled source it is necessary to specify the relationship (transfer function) between the controlling voltage or current and the source's output. The simplest version is a constant gain – the source's output is the controlling value multiplied by the gain. It is also possible to specify the coefficients of a polynomial (a type of mathematical expression) relating the output to the input, however, use of mathematical expressions is better done with a behavioural source, which we will discuss soon. This option is mainly provided to support legacy models. For voltage-dependent sources only, it is possible to define the input-output relationship using a piecewise-linear lookup table – pairs of numbers specify input voltage and corresponding output with that input.

Fig.6 shows an LTspice schematic that illustrates use of controlled sources. `V1` outputs a 1V, 1kHz sinewave across resistor `R1`. The voltage across `R1` is used to control the voltage-dependent voltage source `E1`. `E1's` gain is 5, so the output will be a 5V, 1kHz sinewave. The current through `V1` and `R1` is used to control the current-dependent voltage source `H1`. The waveforms from the simulation are shown in Fig.7.

Ammeter

In Fig.6 we see a use for voltages sources in SPICE that is not immediately obvious – as ammeters. A 0V voltage source behaves like a short circuit, so has no effect if inserted into a wire, but can then be used by a current dependent source to control its output. In Fig.6 the voltage source `Vmeas` is used in this way. The control for `H1` is specified as `Vmeas 5000` – this means: use the current through voltage source `Vmeas` and multiply by the gain `5000` to obtain the output voltage.

The 1V peak across `R1` will result in a 1mA peak current, which when multiplied by 5000 will produce a peak output of 5V. The gain for an `H1` source is a transresistance (voltage/current). In this circuit we could have used `V1` as the

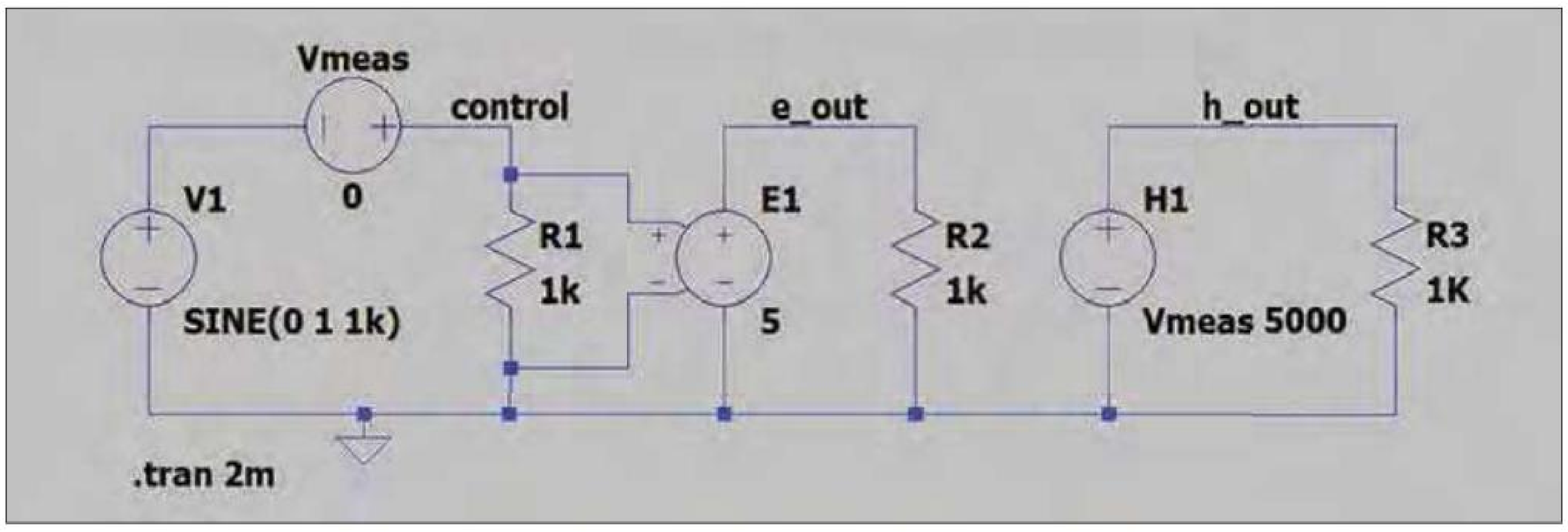


Fig.6. Circuit to illustrate use of dependent sources.

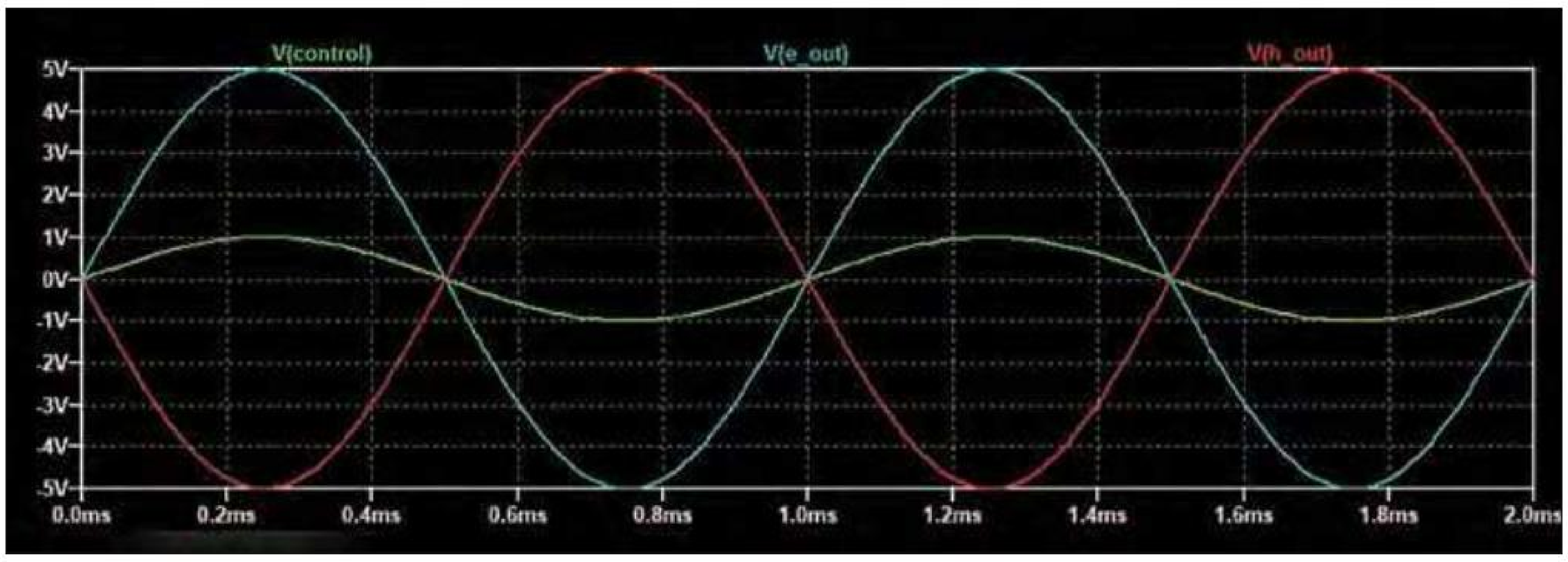


Fig.7. Waveforms from the circuit in Fig.6.

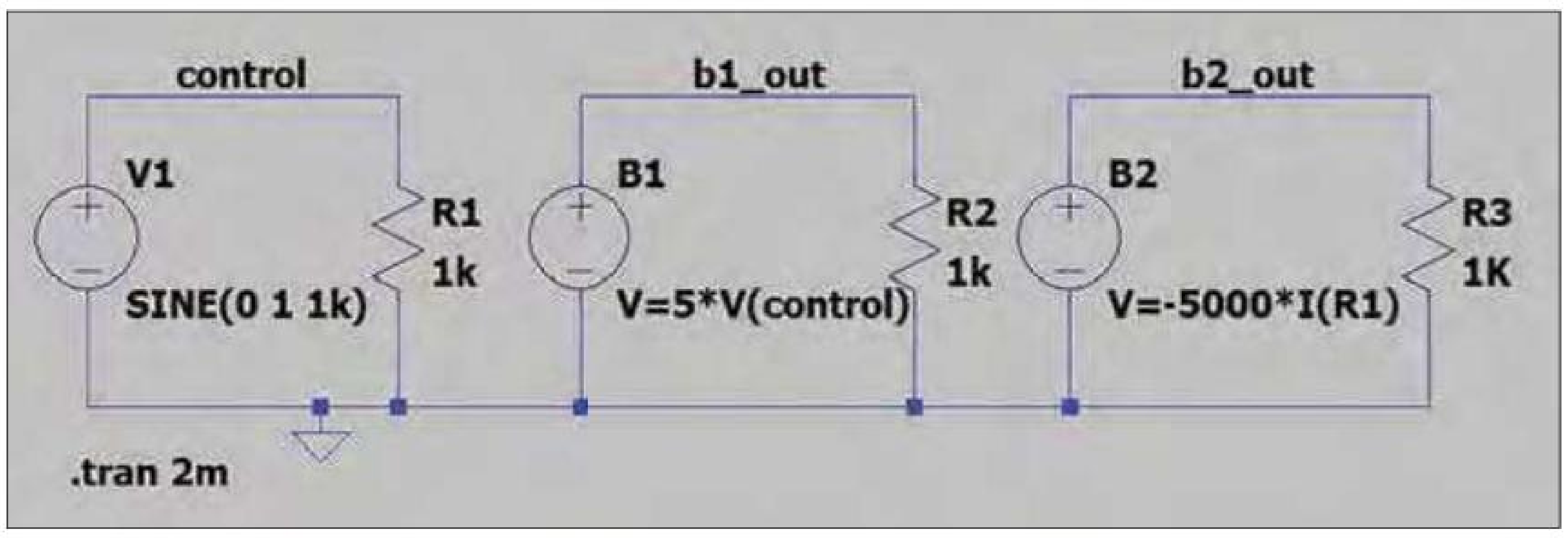


Fig.8. Circuit to illustrate use of behavioural sources.

controlling source, but we included `Vmeas` to illustrate what to do if the current required is not flowing via an existing source. The voltage from `H1` is inverted with respect to the control voltage because the current in `Vmeas` is negative due to the convention used by LTspice for current directions through sources.

Behavioural sources

The `E`, `F`, `G` and `H` sources have relatively limited options for controlling their outputs – the only controlling inputs available are other circuit voltages and currents and, more importantly they are difficult to use beyond simply gains. Much greater flexibility is provided by the behavioural sources (`BV` and `BI` elements) which allow the use of a large range of mathematical expressions to define their output. These expressions can involve time as well as circuit voltages on any wire (to ground), voltage differences (between two wires) and the current in any element (not just voltage sources).

Behavioural sources are configured by setting their value to an equation that specifies their operation. For example, for gains equivalent to those for `E1` and `H1` in Fig.6 we would use the values:

```
V=5*V(control)
V=-5000*I(R1)
```

This is illustrated in Fig.8. The waveforms on `b1_out` and `b2_out` are the same as for `e_out` and `h_out` respectively in Fig.7.

Simulating with WAV files

WAV is a standard audio file format, which was released, by Microsoft and IBM in the early 1990s. WAV files can contain compressed audio data, but they are most commonly used with uncompressed data. Although it is not available via the sources dialog or menus, LTspice `V` and `I` sources can also read files in WAV format, and LTspice can export simulation data to WAV files too.

An audio wave file will typically contain data in a commonly used audio format, that is, in terms of its sample rate, number of channels and number of bits – for example, as stereo CD-quality audio with two channels of 16-bit data at a sample rate of 44.1 kHz. However, WAV is not limited to standard audio formats and can have sample rates in the range 1Hz to 4.3GHz and any number of channels up to 65,536. This means uses of WAV files with LTspice can go beyond working with audio circuits and they can be used for inputting and recording data for a wide range of circuits.

Unlike the PWL data files discussed above, WAV is not directly compatible with spreadsheets, but it can read and written by mathematical software such as MATLAB. Of course, using WAV files for audio circuits means that you can listen to the inputs and outputs of your simulations using a media player application – although you will need the format to be compatible with an audio standard for this to work. Furthermore, other audio generating and processing applications will be usable with your simulation data.

To read a WAV file into LTspice you need to place a voltage or current source on your schematic and change its 'value' to the form:

```
wavefile=filename
```

Where *`filename`* is the name of a WAV file in the same folder as the schematic, or the full path to the file if it is elsewhere. If the path contains spaces it needs to be put in double quotes. Right click the source value and enter the text to set this up. WAV files support multiple channels, so the required channel can be specified in the source value using:

```
wavefile=filename chan=channel
```

Where *`channel`* is the channel number. If it is not specified, then the default is channel 0 (the first channel).

To write a WAV file you need to place an LTspice `.wave` directive on the schematic. This can be done by clicking the .op toolbar button, entering the appropriate text, clicking OK and then clicking on the schematic. The syntax of the directive is:

```
.wave filename nbits samplerate V(net) …
```

Where *`filename`* is the name of the WAV file for the waveforms to be written to – in the same folder, or with a full path, as with file reading. The number of bits used is set by *`nbits`* and can range from 1 to 32. The sample rate is set by *`samplerate`* and, as indicated above, can range from 1 to 4,294,967,295. The settings are followed by the list of net voltages to include in the file (the number listed determines the number of channels). For example, the following will create a file called **output1.wav** with CD format stereo audio (16-bit 44.1 kHz) with the signals on nets `ou1` and `out2` in the two stereo channels:

```
.wave output1.wav 16 44.1K V(out1) V(out2)
```

WAV Example

As an example of using WAV files as input and output to a simulation we will simulate a simple transistor amplifier. The

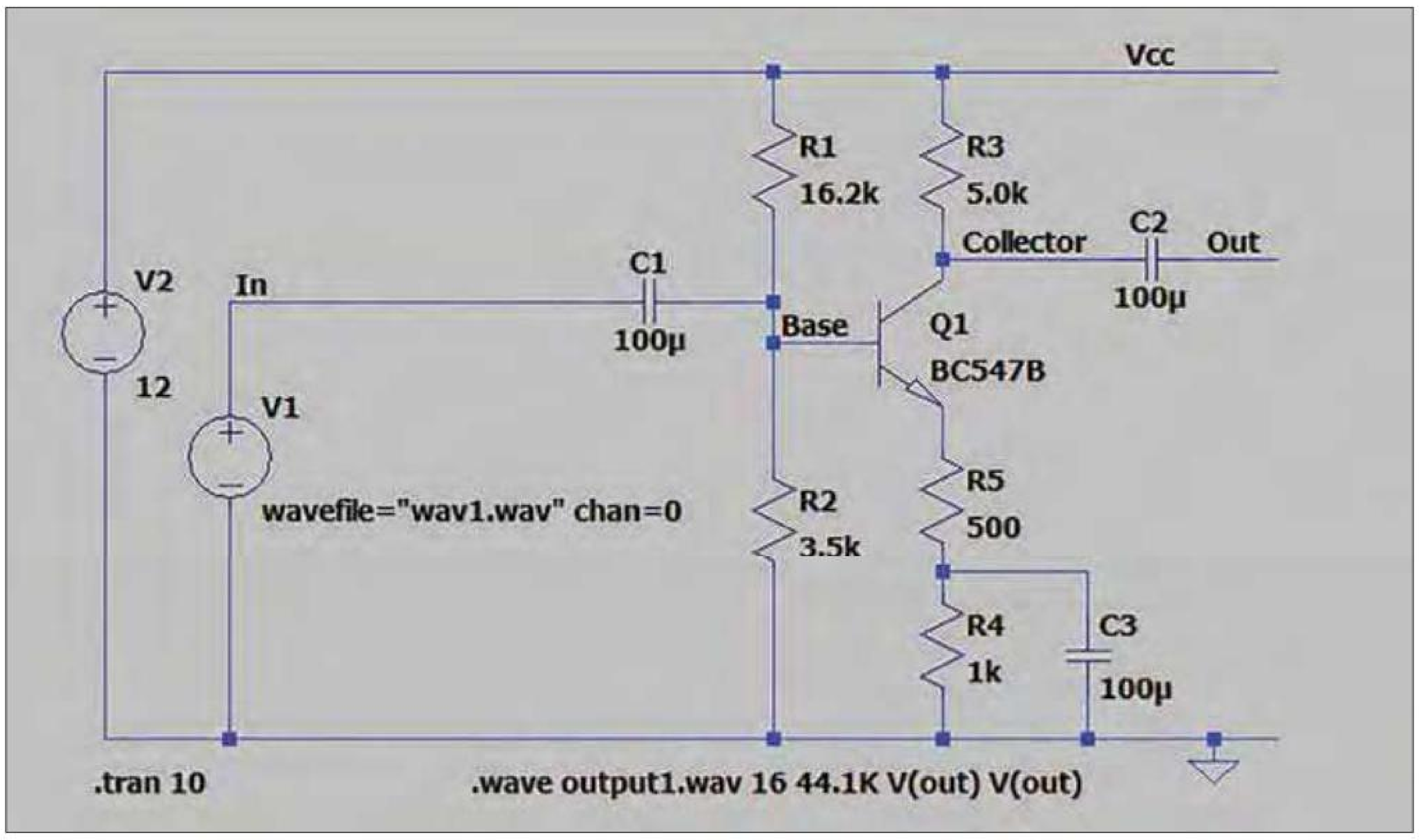


Fig.9. LTspice schematic for simulating a basic amplifier with a signal from a WAV file.

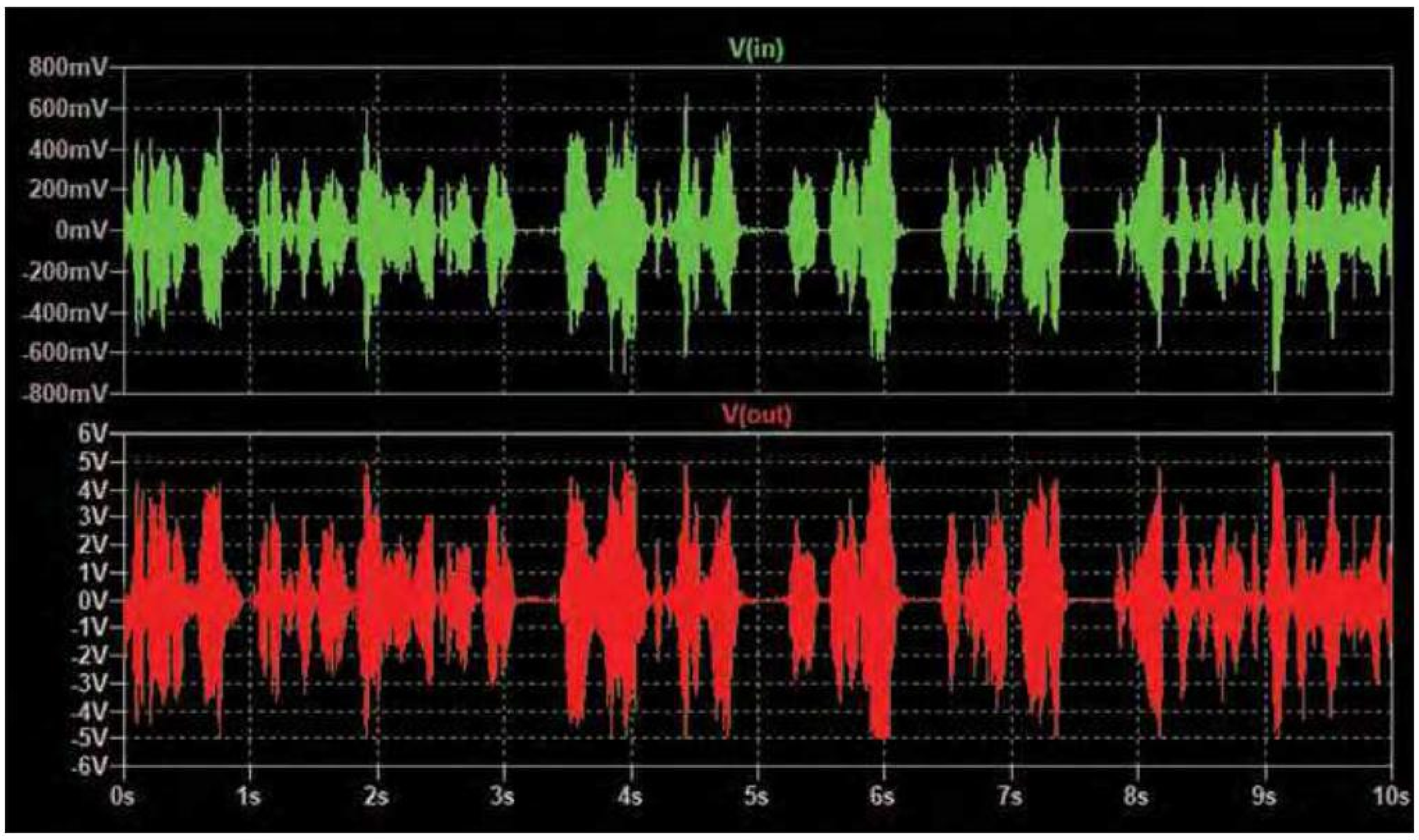


Fig.10. LTspice simulation results for ten seconds of audio (speech) from a WAV file used as input to the circuit in Fig.9, and the resulting output.

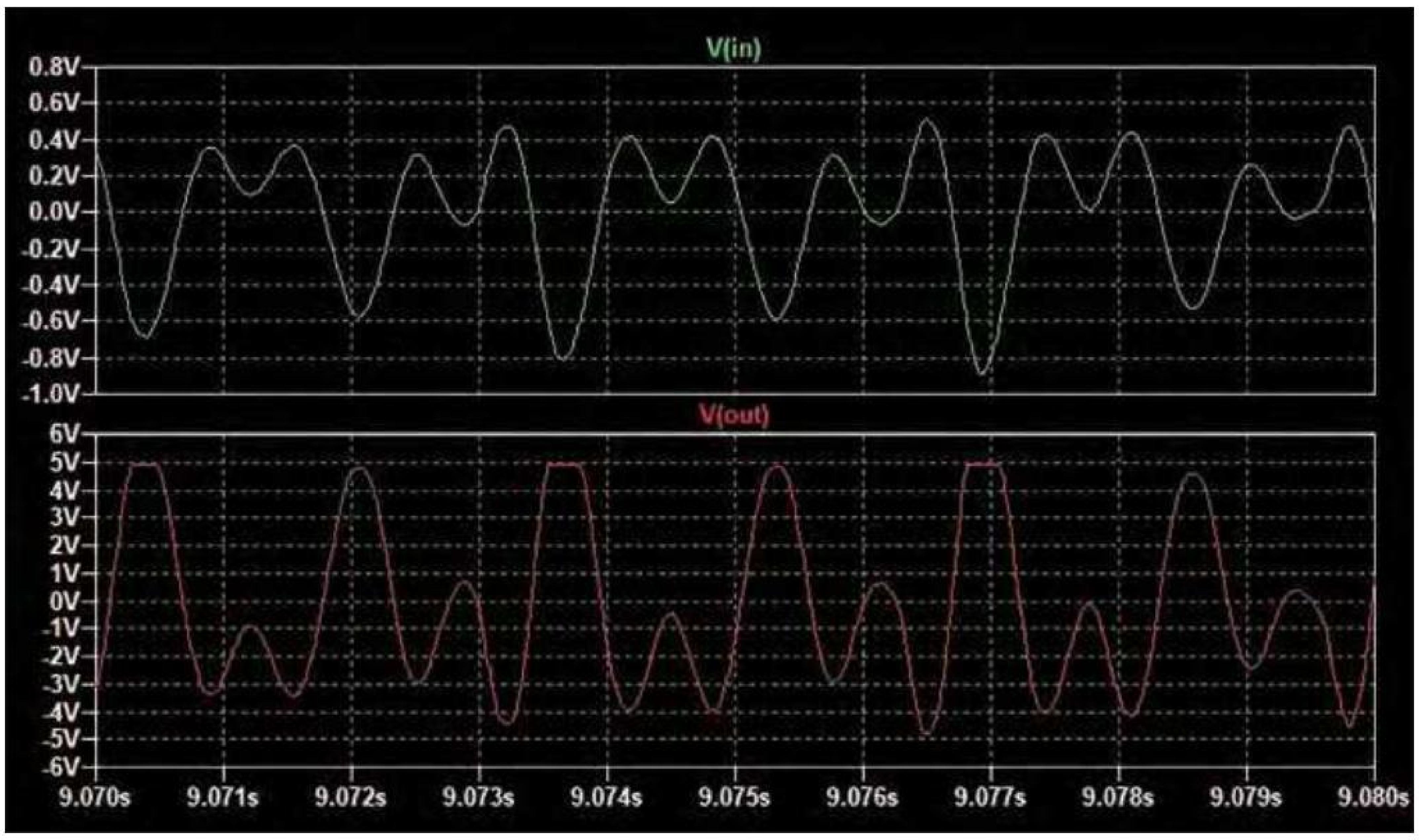


Fig.11. Zoom-in on the waveforms from Fig.10 at around 9s showing an example of clipping of the signal.

schematic is shown in Fig.9 – this is the circuit from the August 2019 *Circuit Surgery* article where we discussed the design of basic common-emitter BJT amplifiers.

There are three changes from the original simulation. First, the value of input signal voltage source (`V1`) has been changed from the original sinewave definition to reading a WAV file (**wav1.wav**). Second, the simulation has been set to run for 10s instead of the original 30ms to match the duration of the audio in the WAV file. Finally the `.wave` directive has been added to the schematic to write the amplifier's output to another WAV file. The settings are similar to the example above except that both channels are being written with the same signal – this will create a file that will play the same waveform through both stereo channels.

Audacity

When working with WAV files in LTspice it is useful to be able to see the waveforms as recorded in the WAV file, as well as recording audio to save as WAV, listening to the files and maybe manipulating the sound in various ways. A particularly useful tool for doing this is the application Audacity. Audacity is described by its creators as a free, open-source, easy-to-use, multi-track audio editor and recorder for Windows, Mac OS X, GNU/Linux and other operating systems. It is available to download from: **www.audacityteam.org**

Opening **output1.wav** in Audacity and zooming to the same range as shown in Fig.11 will reveal that things are not as we might have hoped – see Fig.12. The waveform is much more severely clipped than in the simulation. This is because unlike the PWL files, which can cover any voltage range, LTspice's WAV output is limited to an amplitude of ±1V to conform to the WAV format. This is a problem here because the output is larger than this.

To get around the ±1V limit imposed by using WAV files we need to be able to scale the simulated signal being output so that it stays within this range. To do this we need to know the maximum (peak) value of the waveform and then divide the signal by this value to create a new waveform that stays within ±1V (we say this new waveform is the output 'normalised' to a peak amplitude of 1V). Similarly, when a WAV file is used as input an amplitude of ±1V may not be appropriate for the circuit we are simulating. For the circuit in Fig.9 this is slightly too large, although the clipping produced may provide an opportunity for a listening test – to hear any distortion created by the circuit – but first we have to overcome the clipping caused by the WAV range limits.

Normalising

In some circuits the range of signal we are outputting may be obvious, but in other cases it may be less so. It is therefore helpful if we can measure the actual peak value. You could try to do this manually by looking through the waveform, but this is far from ideal. Fortunately, LTspice has a better means of doing this via the `.measure` (`.meas`) directive. The .measure directive provides a large range of possibilities for obtaining measurements from simulation data; examples include finding the maximum, minimum, average

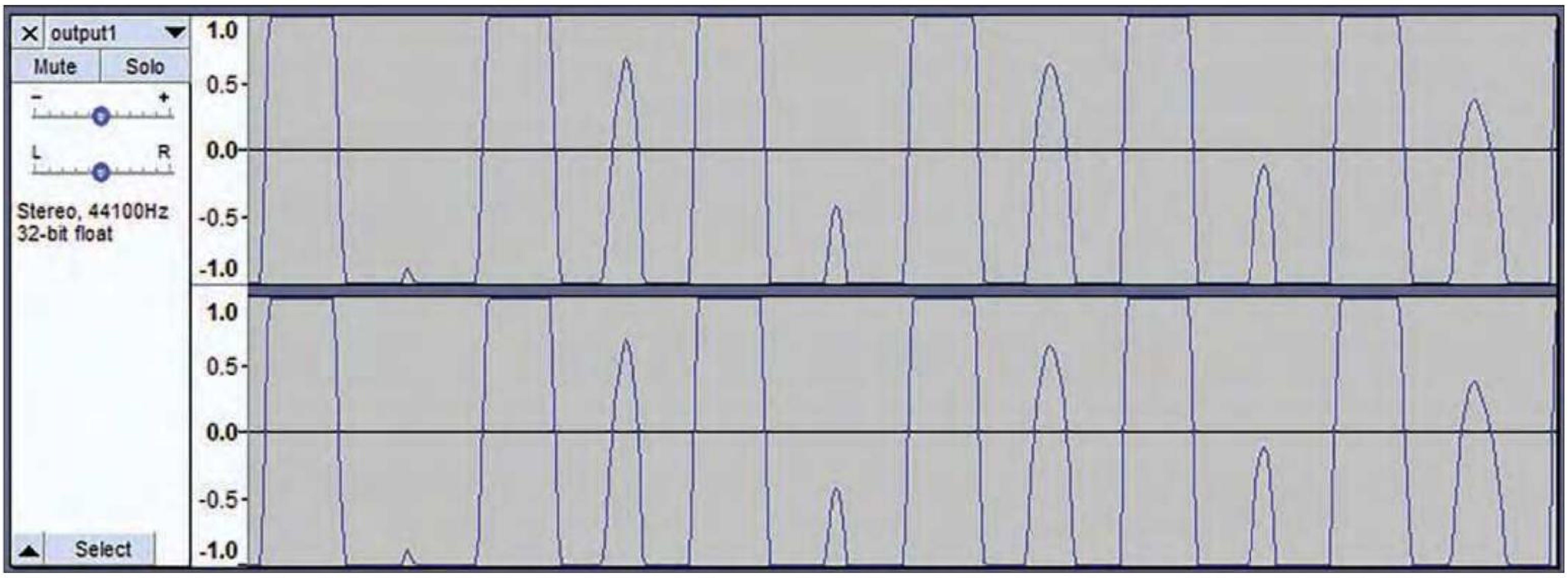


Fig.12. Viewing the WAV file created by the circuit in Fig.9 in Audacity (compare with Fig.11).

or RMS value of a waveform. Mathematical expressions can be applied to circuit signals to which the measurement is applied, increasing the scope of the basic measurements. To find the peak value of a signal we can add the following directive to the schematic (using the `.op` button):

```
.meas peakvalue max abs(v(out))
```

Here, `peakvalue` is just a name give to the measurement result, `max` is the measurement type we are using (find the maximum) and `abs(v(out))` is the value to which the measurement is being applied. This is taking the signal `V(out)` and applying the mathematical 'absolute value' function to it. The abs function removes the sign, so that we find the magnitude of the largest peak in the signal, whether it is negative or positive.

To find the peak value run the simulation and select View > Spice Error Log from the menu. This will open the log file, in which you should find a line similar to the following:

```
peak: MAX(abs(v(out)))=4.99165 FROM 0 TO 10
```

Here we see the peak value is 4.99165 V. The normalisation of signals for WAV output is easily performed using a behavioural source – create a new voltage equal to the signal of interest divided by the peak value calculated using the `.measure` directive. For the circuit in Fig.9, adding the behavioural source shown in Fig.13 does the job. Here, the dividing value has been set to a value slightly larger than the peak. The `.wave` directive also has to be edited to use the new signal (`out_n` rather than `out` in this example). In our example the WAV file name was also changed, to **wave2.wav**

Listening

Using normalisation requires the simulation to be run twice – first to obtain the peak value and then again with the correct normalisation set up to produce the WAV file. The results from Fig.5, modified as described, and loaded into Audacity to display the same range as Fig.8 are shown in Fig.10. We see that the WAV file now matches the LTspice waveform (`v(out)` in Fig.8). The WAV file can now be listened to in comparison with the input, although the difference in this example was not dramatic as only the largest peaks were clipped. Another behavioural source could be added to boost the input signal to cause the circuit to create more distortion, so the effect could be clearly heard. Another experiment worth trying is to reduce the coupling capacitors to a much smaller value (say 1nF), which will cut the gain at low frequencies and make the speech sound different.

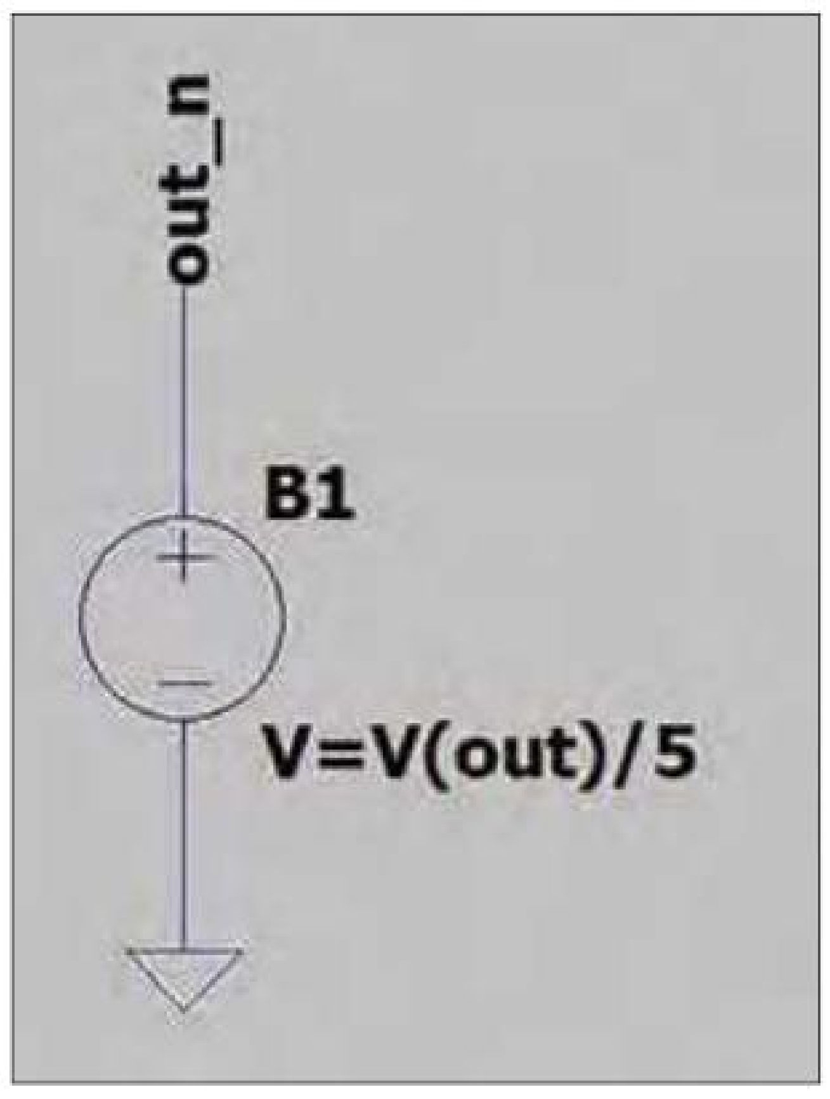


Fig.13. Behavioural source added to the circuit in Fig.9 to normalise the out signal for WAV output.

Simulation files

Most, but not every month, LTSpice is used to support descriptions and analysis in *Circuit Surgery*. The examples and files are available for download from the *PE* website.

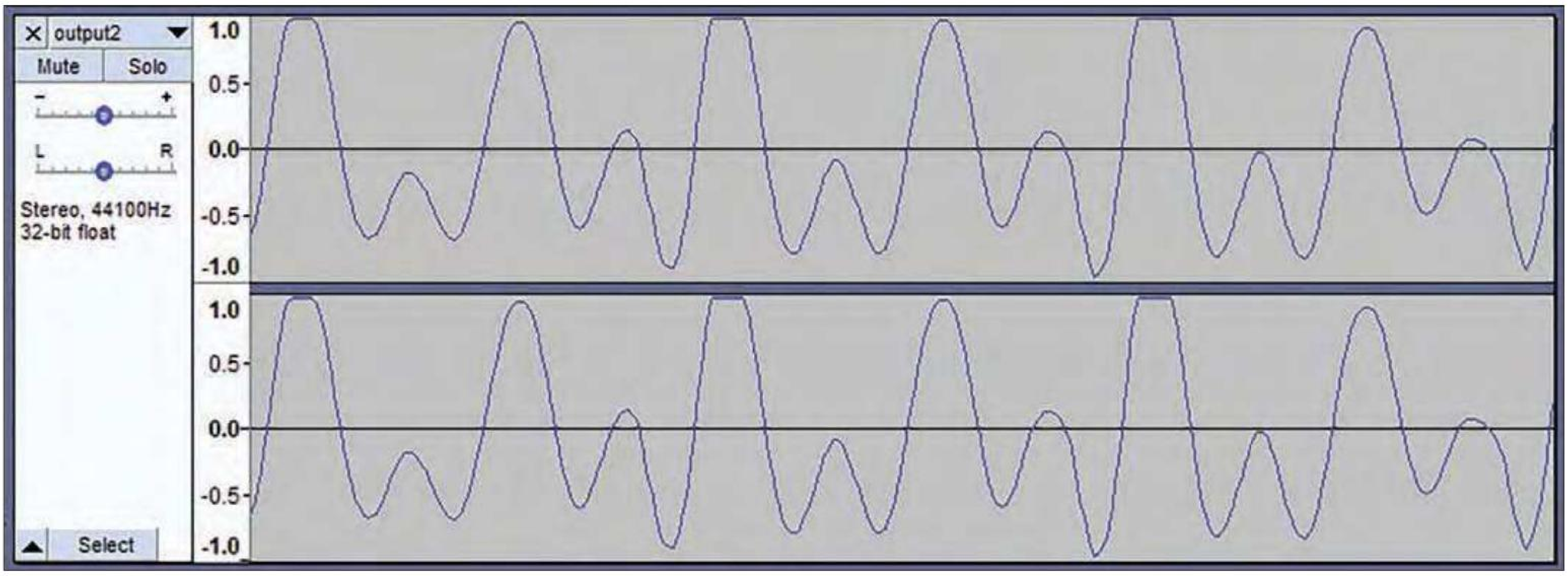
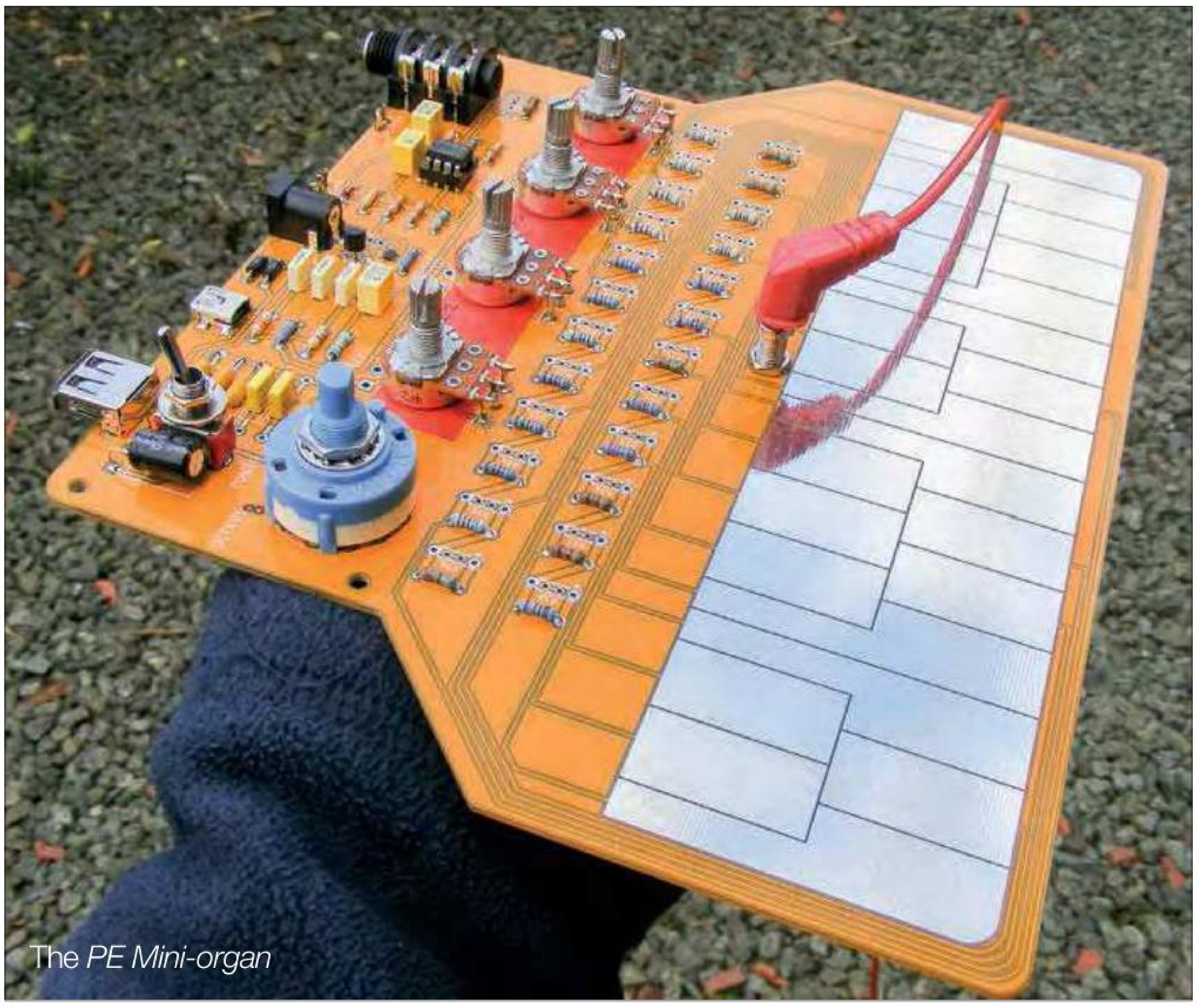


Fig.14. Wave file waveform for the output from the circuit in Fig.9 after normalisation using a behavioural source.

AUDIO OUT

By Jake Rothman

PE Mini-organ – Part 2


The *PE Mini-organ*

Last month, I introduced the *PE Mini-organ*, an easy-to-build, all-analogue, (mostly) through-hole-component design based around a 555 time chip and a PCB keyboard (see above)... oh, and a lot of resistors!

In *Part 1* we covered the design and this month we will run through components and assembly.

Components

Semiconductors

D1, D2	SB40 1A 40V or 1N5817 Schottky rectifier diode
D3	1N4148 standard small-signal
IC1	7555 CMOS timer IC
TR1	BC549C high-H_{fe} NPN small-signal audio transistor
TR2	FDC634P or ZVP2106A low-threshold voltage P-channel MOSFET

Resistors

All standard 0.25W size. Those marked '*' are 5% carbon film. All others, especially keyboard resistors R14 to R38, must be 1% metal-film.

R1	68kΩ*
R2	22kΩ*
R3	4.7MΩ*
R4	30kΩ*
R5	12kΩ*
R6	100kΩ*
R7, R11	47kΩ*
R8, R12*	2.2kΩ
R9	330kΩ*
R10	2.2MΩ*
R13	Not used
R14	62kΩ
R15, R16	3.9kΩ
R17, R18	4.3kΩ
R19, R20	5.1kΩ
R21	5.6k
R22, R23, R24	6.2kΩ
R25	6.8kΩ
R26, R27	7.5kΩ
R28	8.2kΩ
R29, R30	9.1kΩ
R31, R32	10kΩ
R33	11kΩ
R34, R35	12kΩ
R36, R37	3kΩ
R38	15kΩ
R39	Not used.

R40 to R63 on the board are positions for possible trimming parallel resistors, generally not needed.

R64 to R69	Not used
R70	1MΩ

Potentiometers

VR1	10kΩ linear – tuning
VR2§	220kΩ anti-logarithmic – vibrato speed
VR3	100kΩ logarithmic – vibrato depth
VR4§	4.7kΩ anti-logarithmic – volume

(Note: anti-logarithmic potentiometers are available from Tayda or the *PE* special kit.)

Capacitors

C1, C2, C3	150nF 5mm box polyester
C4, C7, C11	470nF 5mm box polyester

C5§, C6§, C8§, C10§ 10nF 5% tolerance or better, C0G/NP0 ceramic, polystyrene or polypropylene. The PCB will accommodate axial or radial types. These are available in a special kit.

C9	470µF 16V radial electrolytic
C12	1nF ceramic 10%
C13	470pF ceramic 10%

SW1	Miniature PCB-mounting SPDT toggle switch Rapid 75-0125
SW2	4-pole 3-way rotary switch make-before-break PCB mounting (or cut tag eyelets off) Lorlin or Taiwan Alpha SR2612-0403-38FS (Rapid 79-0215)

Connectors

2.1mm DC connector PCB mount (Rapid 20-0970)

Solid metal uninsulated 4mm banana socket (Rapid 17-0597)

Standard USB A socket

USB 2.0 mini B jack (Mouser 490-UJ2-MBH-1-SMT)

Mono or Stereo 6.3mm PCB-mount jack socket

Loudspeaker

50Ω to 80Ω§ 67mm minimum. NOS ITT 50Ω 5 × 3-inch speakers in special kit. These are also available from Breconjess.co.uk

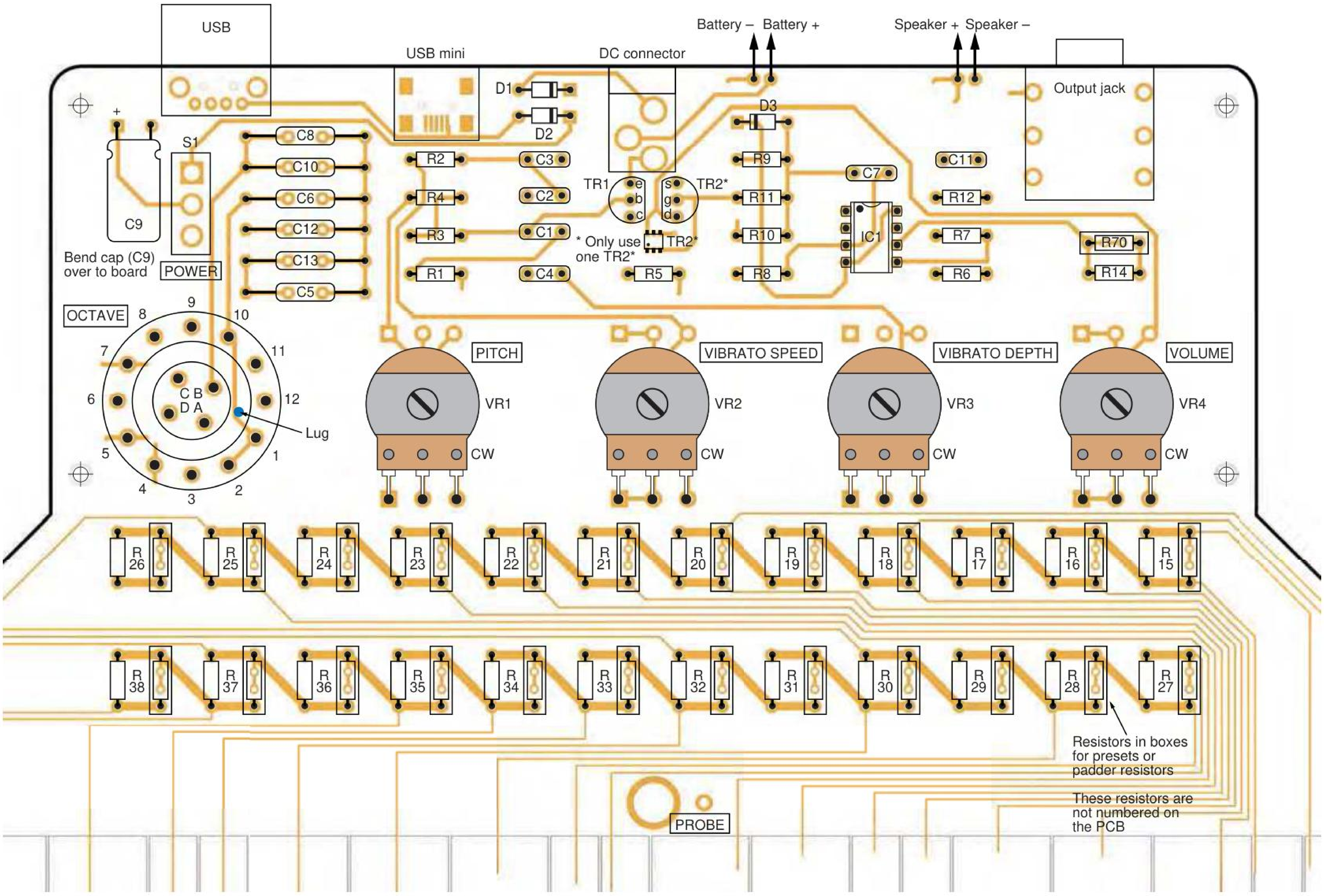
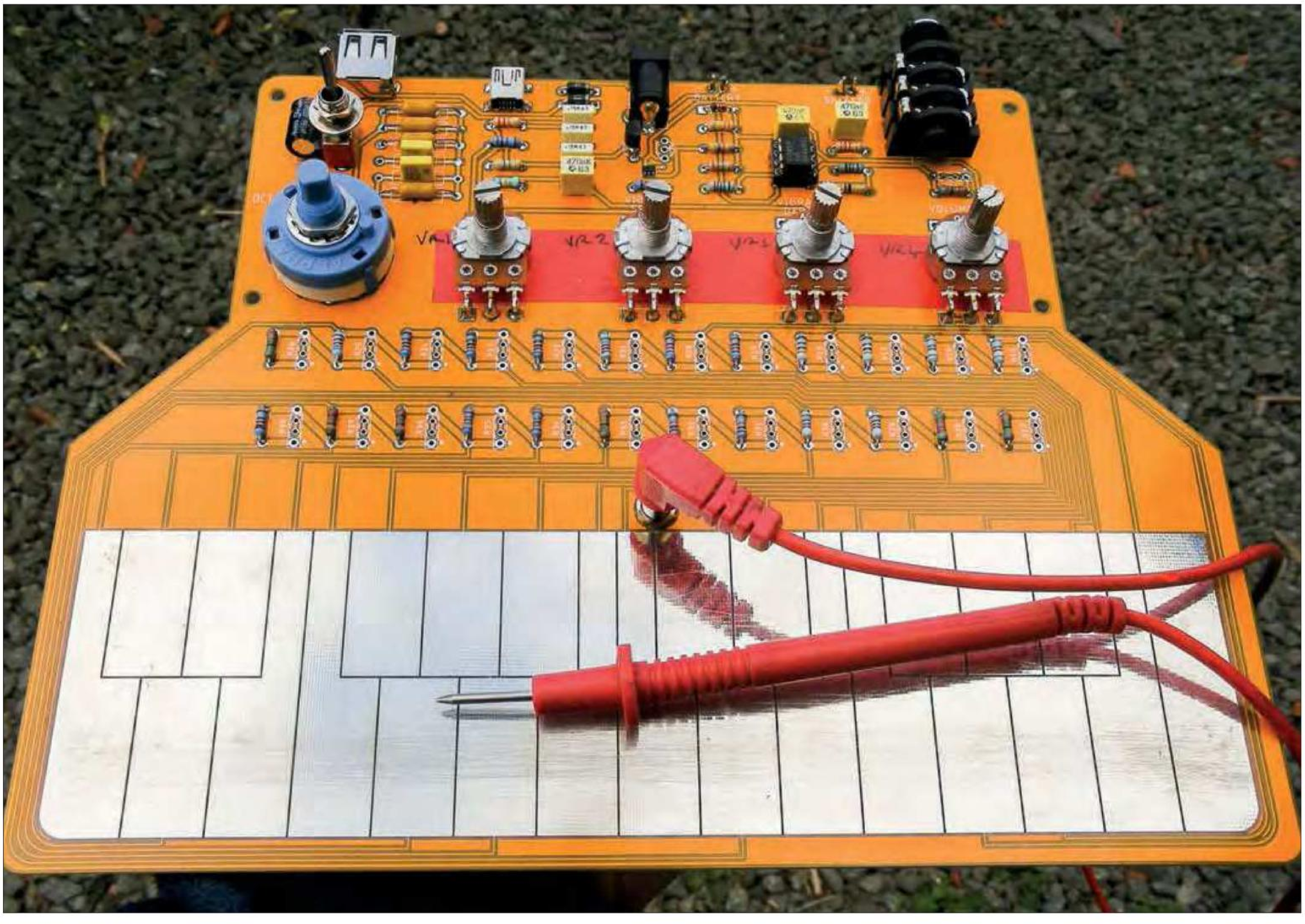

USB
USB mini
DC connector
Battery – Battery +
Speaker + Speaker –
Output jack
D1
D2
D3
S1
C9
Bend cap (C9) over to board
POWER
C8
C10
C6
C12
C13
C5
R2
R4
R3
R1
C3
C2
C1
C4
TR1
e b c
s g d
TR2*
* Only use one TR2*
TR2*
R5
R9
R11
R10
R8
C7
IC1
C11
R12
R7
R6
R70
R14
OCTAVE
1 2 3 4 5 6 7 8 9 10 11 12
C B D A
Lug
PITCH
VIBRATO SPEED
VIBRATO DEPTH
VOLUME
VR1
VR2
VR3
VR4
CW
R26 R25 R24 R23 R22 R21 R20 R19 R18 R17 R16 R15
R38 R37 R36 R35 R34 R33 R32 R31 R30 R29 R28 R27
Resistors in boxes for presets or padder resistors
These resistors are not numbered on the PCB
PROBE

Fig.9. *PE Mini-organ* PCB overlay. (The keyboard section has been cropped, but it contains no components.)

Fig.10. Completed board – it's so good looking that it's worth making a perspex panel for it!



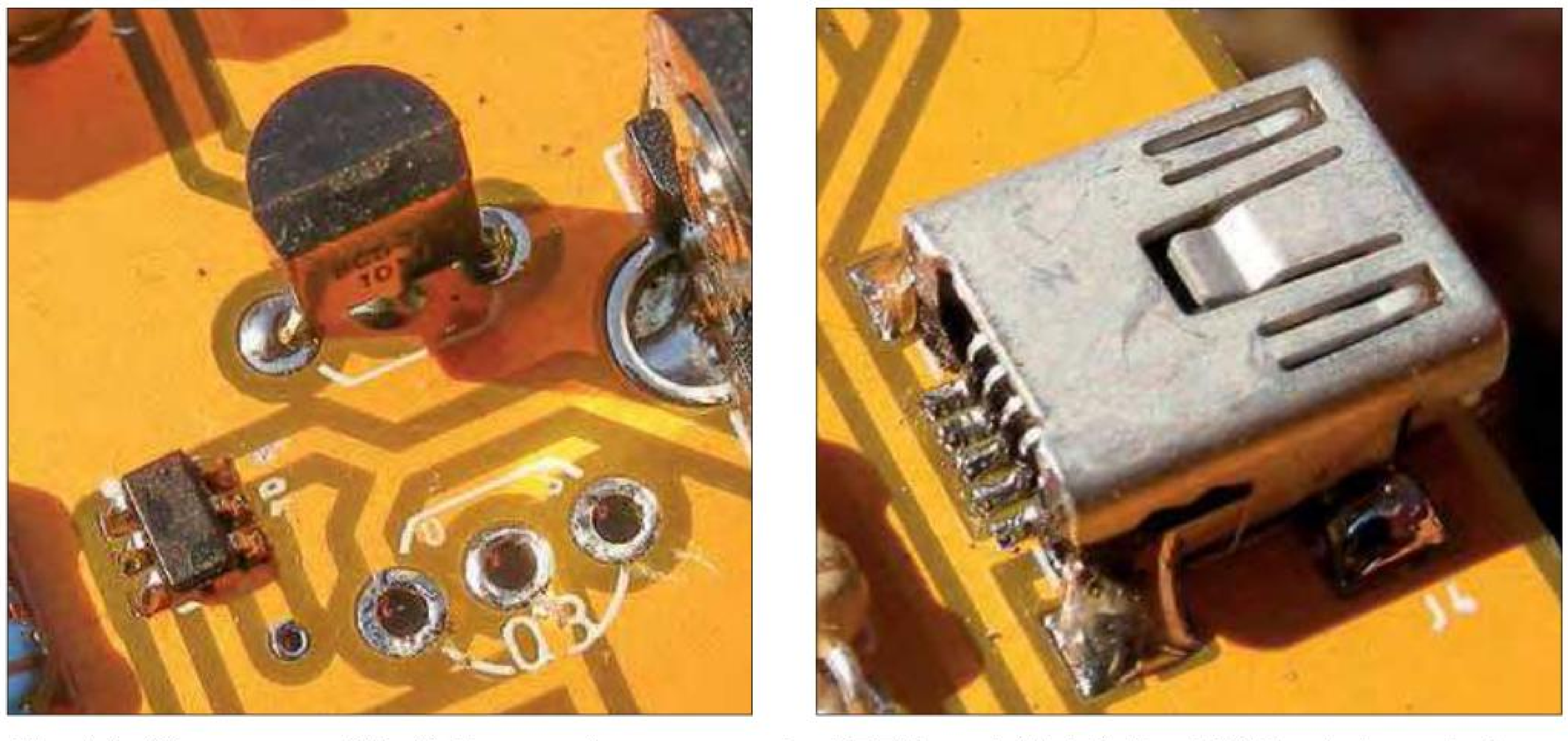


Fig.11. Close-up of (left) the surface-mounted FET and (right) the USB-mini socket.

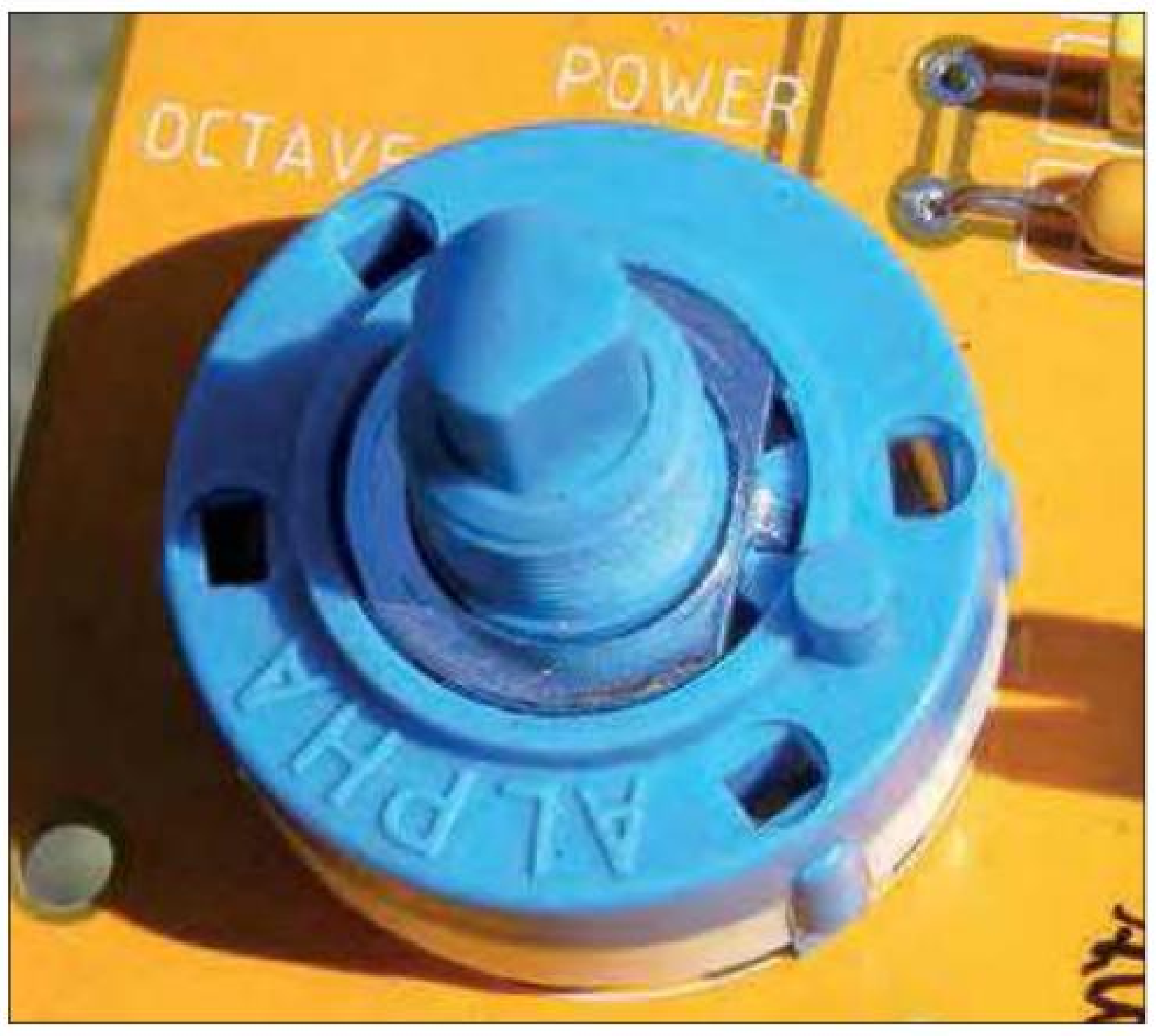


Fig.12. Rotary octave switch mounting – note the stop washer and position of tab.

Optional output transformer Xicon 42TU200-RC (Mouser) or Eagle LT726 (J Birkett's in Lincoln: 01522 520767).

A PCB (AO-0720-01) and a kit (AO-0720-02) of the hard-to-get parts: four 10nF 5% caps, the 50Ω speaker and the two anti-logarithmic pots are available from the *PE Shop*. The parts in the kit are marked '§' in the components list.

Construction

The whole point of this design is that it's easy to make – there's lots of space, as shown in Fig.9 and Fig.10. The board area is four times that of the commercial version. Solder in the usual sequence: if used, SMT parts first, (so you can get round them with the iron), then low-profile parts such as resistors and diodes. The chip socket and axial capacitors should be next, and then finally all the stuff that sticks out; inserting it in order of height, such as the transistors, radial capacitors and sockets. The pots and switches should be last.

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Note that there are multiple outlines on the pots and octave capacitors to facilitate the use of different types. If the correct PCB mount pots cannot be obtained it is a simple matter to insert 0.15-inch Veropins and solder standard 16mm Alpha pots to these. Remember to cut the shafts on the rotary controls to the right length to suit the knobs and front panel used before soldering. It's not a good idea to wield a hacksaw on a completed PCB! (The PCB uses plated-through-holes, which can make de-soldering a trial.) Remember the board costs more than the components, so if a component must be removed don't worry about damaging it; cut the lead-out right against its body if necessary. Fig.11 shows close-ups of the optional SMT components (USB-mini socket and TR2).

Be careful mounting the rotary switch (see Fig.9 and Fig.12 to get the numerical position right). If you get it wrong it's a pig to unsolder. Also, watch out that you get the indentation stop washer (with its protruding tab) in the right position. If the switch just goes round and round or moves less than three positions then it's in the wrong hole.

The height of the components is critical if a front panel is to fit properly. C9 may have to be bent over as shown in the photos. The rotary switch is the tallest and the other switch and the pots will need extra nuts to bring them up to the same level.

Probe

The stylus probe is made with an old test meter lead that is plugged into a banana socket soldered into the board (see Fig.13). If the end is sharp, it is best to round it off a bit with a file. I have seen Stylophone keyboards almost worn away by scratchy probe tips. The boards have a bright tin coating that seems to resist abrasion.

Case

For the moment I'll leave the case details – but do remember to allow space for the protruding speaker magnet.

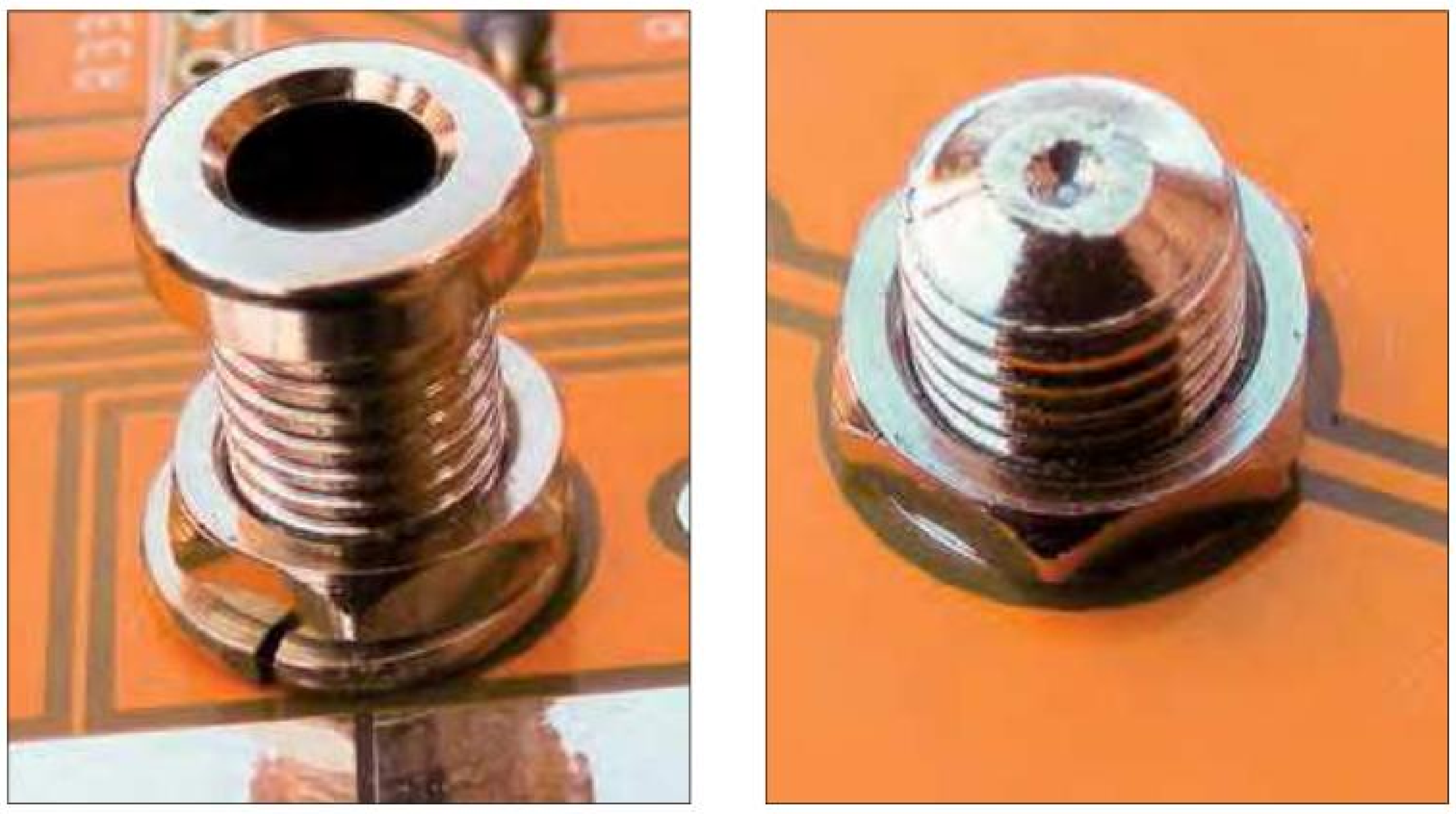


Fig.13. (Left) Use a metal 4mm socket to plug in a probe lead for the keyboard (note the nut spacing); (right) The socket can be soldered into the board – the protruding cable terminal (under the board) has been cut off.

Make it with Micromite

Phil Boyce – hands on with the mighty PIC-powered, BASIC microcontroller

Part 18: Animated eyes for the Micromite Robot Buggy

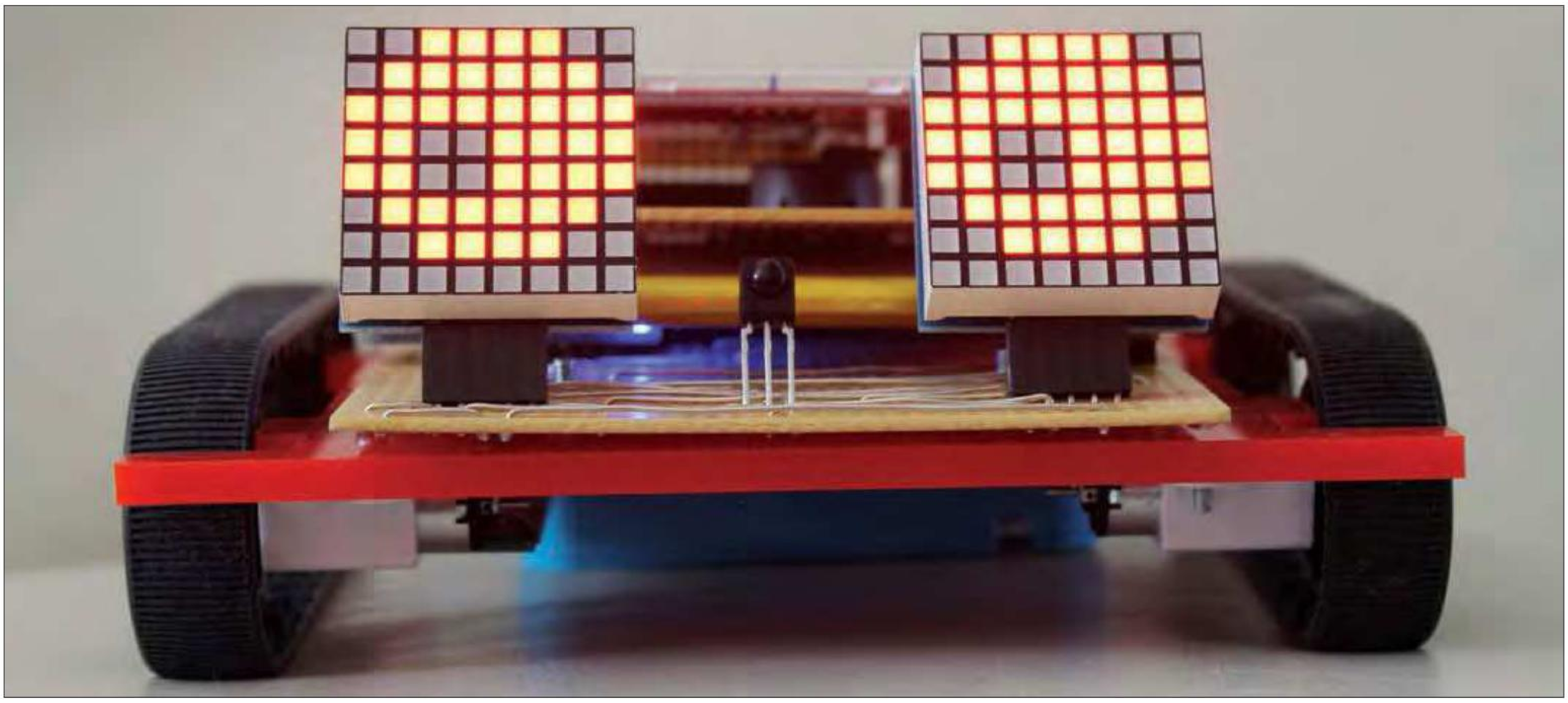


Fig.25. Adding a pair of animated eyes (8x8 LED matrix modules) and an IR receiver to the front of the *MRB's* daughterboard.

In the previous two articles we explained how to assemble and test the chassis for the *Micromite Robot Buggy* (*MRB*). This month, we will begin to add some personality to the robot by attaching a pair of animated eyes. This will involve adding two LED 8×8 matrix modules (and some wire links) to the front of the existing daughterboard. While we are making the necessary modifications we will also add an IR receiver to provide another method of controlling the robot. The end result of these two modifications is shown in Fig.25.

Circuit diagram

Now examine Fig.26, which shows the schematic, comprising two blocks:

1. IR receiver
2. Two LED matrix modules (eyes).

Micromite code

The code in this article is available for download from the *PE* website.

Assembly is just a matter of connecting these additional hardware items to the correct Micromite pins (and power).

The IR receiver is the standard TSOP device that we have used in previous articles throughout this series. It only requires a 5V/0V supply, and a connection to Pin 16 – the Micromite's IR input pin.

Each of the animated eyes is based on an SPI LED matrix module, similar to the one we explored back in *Part 12* (January 2020). Fig.27 shows the front and the back of the LED modules we are using. These two modules are daisy-chained to each other, meaning that the DOUT pin on the first LED module (left eye) is connected to the DIN pin on the second module. All other pins on each matrix module are effectively paralleled together.

The left eye's data input pin (DIN) is fed from the Micromite's SPI data out pin (pin 3), with enough data-bits sent from the program code to fill two matrix modules (because they are daisy-chained). The CLK pins are fed from the Micromite's SPI CLK pin (pin 25).

For SPI data to be received by the matrix modules, the CS pin must be at a logic low level. The CS pin from each module is therefore connected to an available I/O pin to allow this software control – here we have used pin 21.

The LED matrix modules could be soldered directly to the stripboard; however, we have used two 5-way sockets (JS6 and JS7) making it easy to replace them should the need arise (for example, to swap them out for a different LED colour).

Note that the DOUT pin is not present on the module's row of five pins; it is presented in a socket on the top edge of the matrix module. Instead, however, we will attach a wire link to the DOUT solder position mid-way on the back of the module (this can be seen in Fig.27). To assist with assembly, the other end of the DOUT wire link is soldered to a

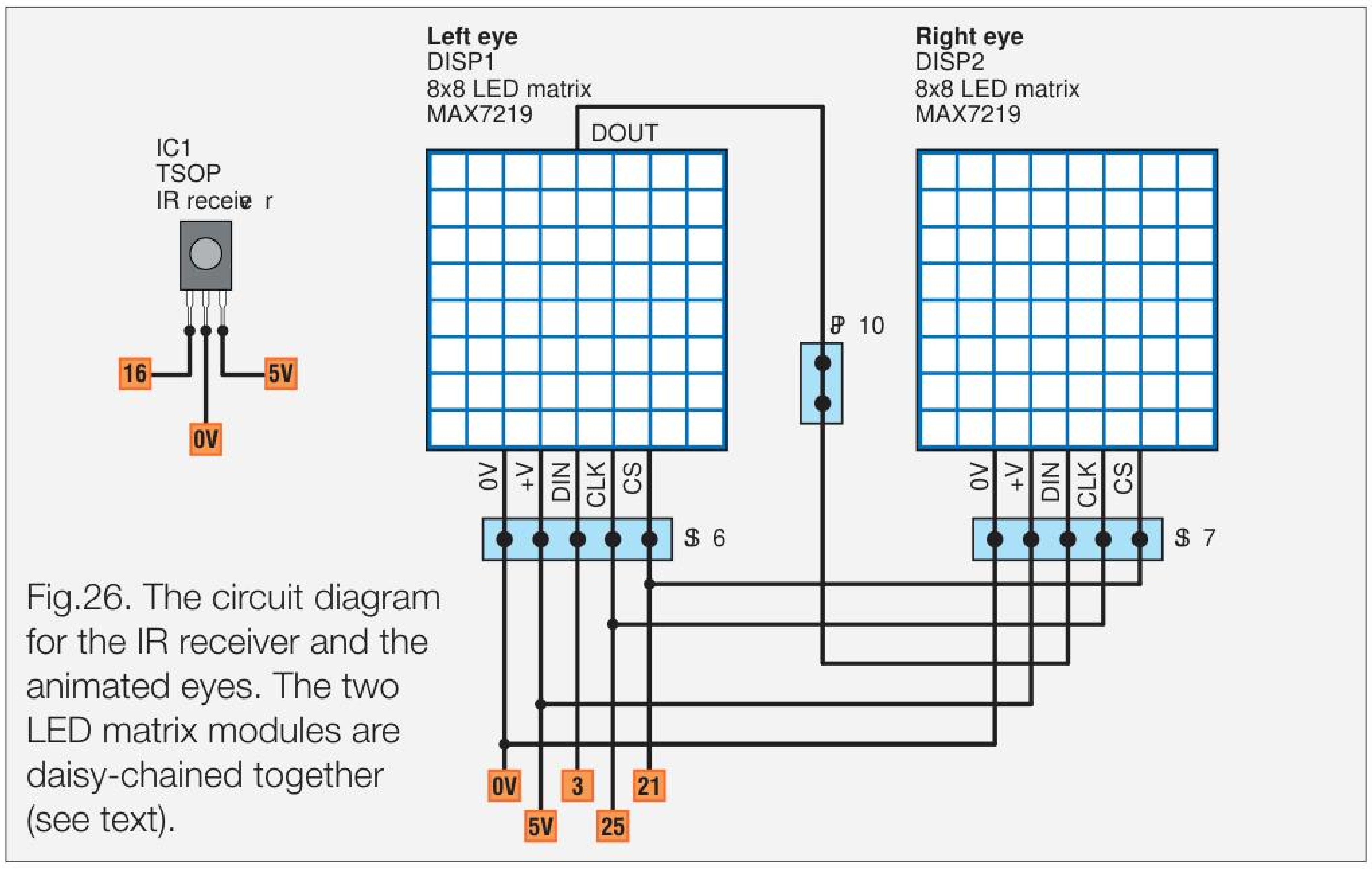


Fig.26. The circuit diagram for the IR receiver and the animated eyes. The two LED matrix modules are daisy-chained together (see text).

modified 2-way header pin (JP10).

The LED matrix modules can operate from either 3.3V or 5V. We have used 5V since it allows for 'brighter eyes'.

Stripboard modifications

Fig.28 shows the modifications (in red) required to your existing daughterboard. There are 10 track cuts, 14 wire links, two 5-way sockets, one 2-way pin header, and one TSOP IR receiver to be installed.

To begin with, you will need to partially disassemble your *MRB* – this is just a matter of unplugging any connected modules (including the *MKC (Micromite Keyring Computer)* and BT (BlueTooth) module from the underside). Then remove the four M3 nuts that secure the daughterboard to the chassis. Next, separate (unplug) the daughterboard from the two motor connectors.

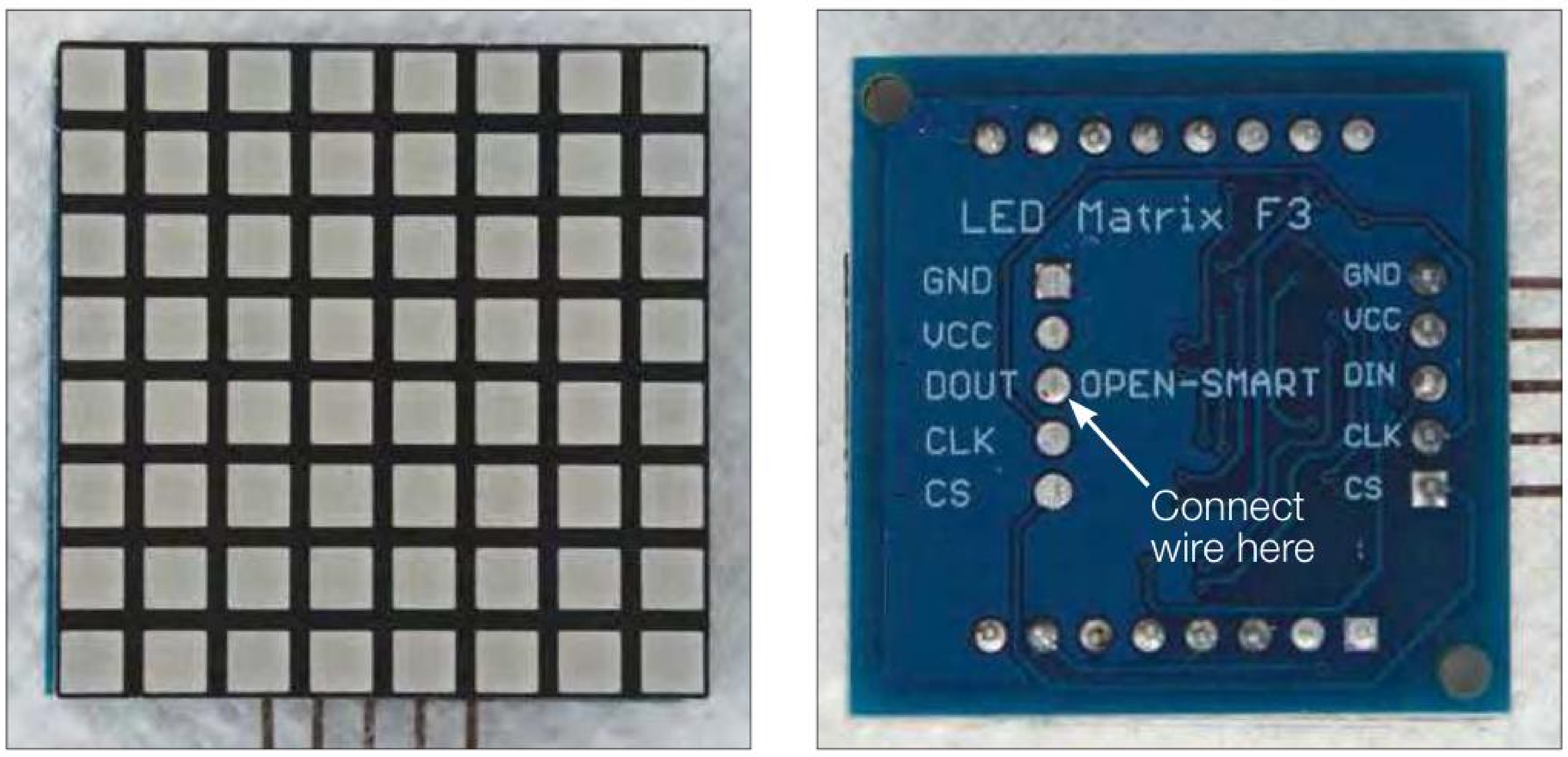
Once the daughterboard has been removed, mark out the ten required track cuts shown in Fig.28. After double-checking you have the correct positions, make the cuts – ensuring the cuts are the full width of the track and that you have left no copper burrs that could short tracks.

Next, mark out, check and install the 14 wire links. All but one of these links are towards the front of the robot, so be careful not to omit the single wire link between the *MKC* pins/sockets (NN14-NN35).

The IR receiver (IC1) has to be inserted with the correct orientation. The rounded part of the IR body faces the front of the robot (as can be seen in Fig.28, and also the photos of Fig.29 and Fig.30).

The two 5-way sockets (JS6 and JS7) are next. These are mounted at a shallow angle to allow for the eyes to face slightly upwards rather than directly forward (see Fig.29). Be sure to get their positions exactly as shown in Fig.28.

The two-way header pin (JP10) is installed (facing upwards) in the relevant position in track 32. Its purpose is to make it easier to solder the wire link that is used to connect to the DOUT point on the back of the left eye. JP10's pin at position I32 is cut flush after soldering (see Fig.30), leaving a single pin onto which to solder the DOUT wire link. The final connection to install is the actual DOUT wire link. First, insert an LED matrix module into JS6 (the left eye) and then solder one end of a short length of wire to the DOUT point on the back of the matrix. Finally, solder the other end of the wire link to JP10 (refer to Fig.30).



Connect wire here

Fig.27. The front and back of the LED matrix modules that we are using for the animated eyes. Note the position of the DOUT pin which will be used on the left eye.

Testing

Begin by doing a thorough visual check of the daughterboard before re-mounting it back onto the chassis. Ensure that you secure it with the four M3 nuts, and then insert your *MKC* and BT modules from the underside. Next, insert the other LED matrix module (right eye) into JS7. Carefully insert the LiPo battery and power up the *MRB*. Then make a connection to your terminal app (such as TeraTerm). With an established connection you can install this month's demonstration program onto your *MKC*. The file you require for this test is: **AnimatedEyesTestCode.txt**, which can be downloaded from the July 2020 page of the *PE* website.

Once installed, RUN the program and you should see an animated affect appear on the two LED matrix modules. If not, then you will need to recheck the modifications you made on the daughterboard. If the left eye shows animation, but not the right, then check the DOUT wire link, because this will be the likely issue.

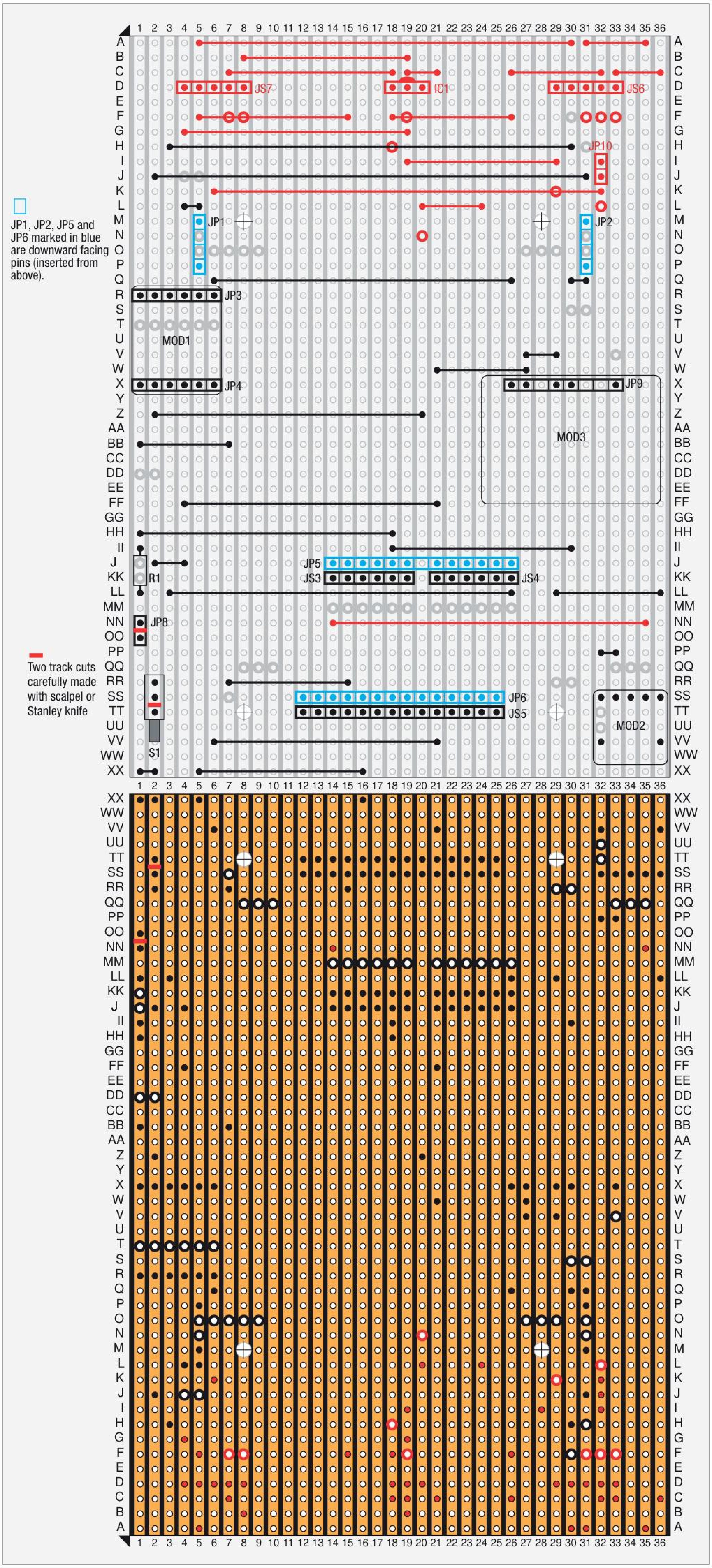
Now grab a remote control transmitter, point it towards the front of the *MRB* and press any button. You should see two numbers appear on the terminal screen – these represent the IR device code, and the IR keycode (as discussed in a previous article). If you don't see any numbers, first try some other remotes; and only then if you're still not seeing anything, check the three connections relevant to the IR TSOP receiver (IC1).

Notes about the demo program

It is worth taking a quick look at the demo code, but do not worry if you don't fully understand it. It comprises two main parts. One section is a single interrupt routine that deals with the IR remote control – you should recognise it easily enough (and it is commented too). The other part of the code will look more complex, but it is essentially a `DO...LOOP` that sends the required data to the LED matrix modules using the SPI communication protocol. There is an initial setup for the LED modules, which sets certain parameters, and then it is just a matter of sending the required LED 'pattern' data (this method was discussed in *Part 12*). As previously mentioned, if you don't fully understand the code, simply use it for now to check that the animated eyes (and IR receiver) are functioning correctly.

Next month

The whole idea behind the *MRB* is to bring together many of the individual lessons learnt so far throughout the *Make it with Micromite* series, and combine them into a fun, yet highly customisable project. Our robot buggy currently implements a useful collection of hardware features



JP1, JP2, JP5 and JP6 marked in blue are downward facing pins (inserted from above).

Two track cuts carefully made with scalpel or Stanley knife

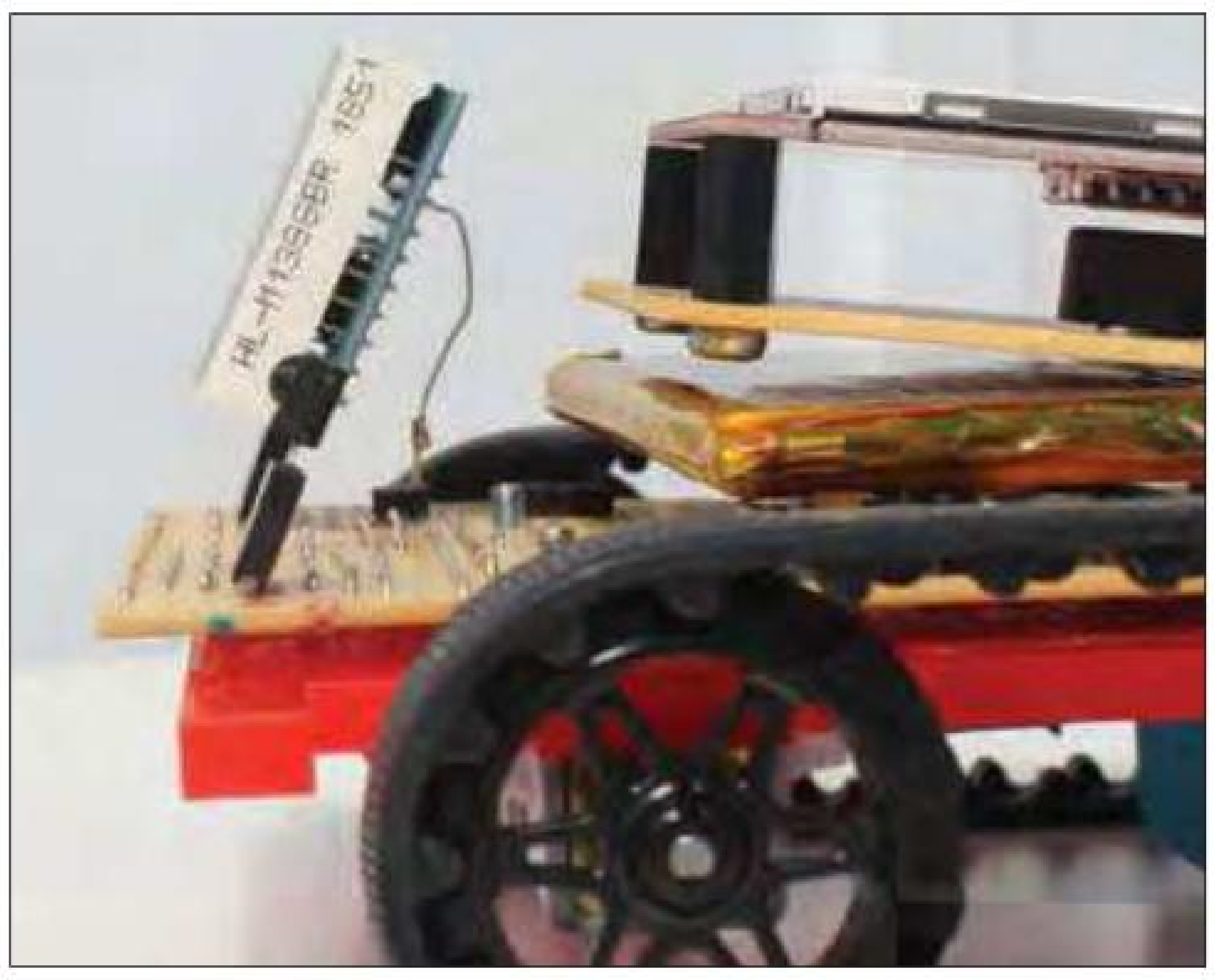


Fig.29. Two 5-way sockets (JS6 and JS7) are soldered into place at a slight angle to make the eyes face upwards a little.

that provide the potential for it to behave in many different ways. Ultimately, the robot's behaviour is all down to the program code running on the Micromite (here the *MKC*), so next month we will have some fun with MMBASIC and explore ideas for controlling your robot buggy.

In the meantime, why not modify this month's demonstration code to allow your robot to be moved by an IR remote control.

Have fun, and do stay safe!

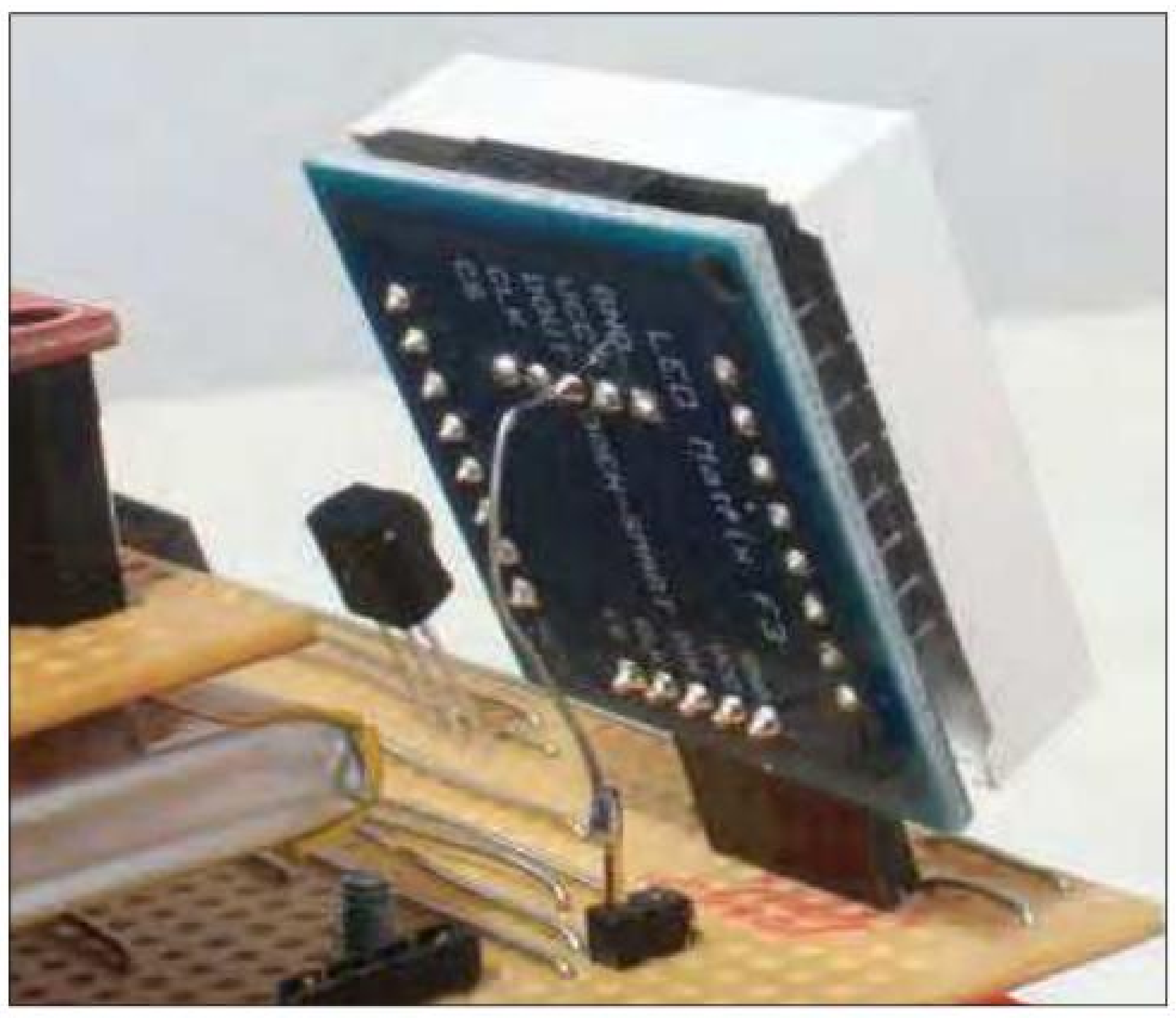


Fig.30. A 2-way pin header (JP10) is used to solder a wire link to the DOUT point on the back of the left eye. Looks fiddly, but it's actually straightforward.

Sourcing the MRB chassis

The *MRB* we have described uses an acrylic chassis, but the current pandemic means we don't have access to our usual laser cutter. So, we are now offering an equally good CNC-milled version made from 2mm-thick PCB material available from: **micromite.org**

Questions? Please email Phil at:
contactus@micromite.org

Fig.28. (left) The existing daughterboard needs to be modified with the items shown highlighted in red. (Note that the two track cuts marked in red at NN-OO 1 and SS-TT 2 are *not* new – you should have added them last month.)

PIC n' Mix

Mike Hibbett's column for PIC project enlightenment and related topics

Part 1: Introducing the PIC18 family

In this month's article we will introduce a new series that dives into the PIC18 microcontroller family, looking at the device's capabilities, software development tools and building up our own development board. We will explore how designing a project based around Microchip's PIC processors complements the use of an Arduino platform, and how there are 'for' and 'against' arguments related to each development approach. These articles will be aimed at people already familiar with basic microcontroller development, on platforms like the Arduino. While we will attach a variety of peripherals to our processor board, the key focus is going to be on using the PIC itself.

Before we dive in, let's look at the range of processors available from Microchip. Although you rarely find PIC processors in hobbyist development boards, they do find their way into some mission-critical applications. We've seen them in automotive systems and data-centre power supplies, where high reliability and long availability of parts is essential. Microchip keep their parts available for purchase so long as there is customer demand – the original PIC16C63, which we used back in the early 1990s, is still available – in stock with Digikey!

The Microchip PIC families

Microchip have seven families of processors, not including those acquired from Atmel: PIC10, PIC12, PIC16, PIC18, PIC24, PIC33 and PIC32. These families are grouped by the type of processor

					Peripheral Function Focus																								
					Intelligent Analog								Waveform Control							Timing and Measurements$^{(1)}$							Logic and Math		
Product Family	Pin Count	Program Flash Memory (KB)	RAM (B)	Data EE (B)	ADC (# of bits)	Comp	HSComp	DAC (# of bits)	OPA	PRG	SlopeComp	ZCD	CCP/ECCP	10-bit PWM	16-bit PWM	COG	CWG	NCO	DSM	AngTMR	HLT (8-bit)	16-bit PWM (16-bit)	NCO (20-bit)	SMT (24-bit)	RTCC	TEMP/TS	CLC	MULT	MathACC
PIC10(L)F3XX	6	384–896	64	HEF	8									✓			✓	✓					✓			✓	✓		
PIC12LF1552	8	3.5	256	HEF	10																					✓			
PIC16LF155X/6X	14–20	7–14	1024	HEF	$10^{(2)}$									✓												✓			
PIC16(L)F145X	14–20	14	1024	HEF	10	✓								✓			✓									✓			
PIC1X(L)F157X	8–20	1.75–14	1024	HEF	10	✓		5							✓		✓					✓				✓			
PIC16(L)F153XX	8–48	3.5–28	2048	HEF	10	✓		5				✓	✓	4			✓	✓			✓		✓			✓	✓		
PIC1X(HV)F752/53	8–14	1.75–3.5	128	–	10		✓	5/9	✓		✓		✓			✓					✓								
PIC1X(L)F1612/3	8–14	3.5	256	HEF	10	✓		8				✓	✓				✓				✓			✓		✓			
PIC16(L)F161X	14–20	7–14	1024	HEF	10	✓		8				✓	✓	✓			✓			✓	✓			✓		✓	✓		✓
PIC16(L)F170X	14–20	3.5–14	1024	HEF	10		✓	5/8	✓			✓	✓	✓		✓										✓	✓		
PIC16(L)F171X	28–40	7–28	2048	HEF	10		✓	5/8	✓			✓	✓	✓		✓		✓					✓			✓	✓		
PIC16(L)F176X/7X	14–40	7–28	2048	HEF	10		✓	5/10	✓	✓	✓	✓	✓	✓	✓	✓			✓		✓	✓				✓	✓		
PIC16(L)F183XX	8–20	3.5–14	2048	256	10	✓		5					✓	✓			✓	✓	✓				✓			✓	✓		
PIC16(L)F184XX	14–28	7–28	2048	256	$12^{(3)}$	✓		5				✓	✓	✓			✓	✓			✓		✓	✓		✓	✓		
PIC16(L)F188XX	28–40	7–56	4096	256	$10^{(3)}$	✓		5				✓	✓	✓			✓	✓	✓		✓		✓	✓		✓	✓		
PIC16(L)F191XX	28–64	14–56	4096	256	$12^{(3)}$	✓		5				✓	✓	✓			✓				✓			✓	✓	✓	✓		
PIC18(L)FXXK40	28–64	16–128	3728	256–1K	$10^{(3)}$	✓		5				✓	✓	✓			✓		✓		✓					✓		✓	
PIC18(L)FXXK42	28–48	16–128	8192	256–1K	$12^{(3)}$	✓		5				✓	✓	4			✓	✓	✓		✓		✓	✓		✓	✓	✓	
PIC18(L)FXXJ94	64–100	32–128	4096	–	12	✓							✓												✓			✓	
PIC18(L)FXXK83	28	32–64	4096	1K	$12^{(3)}$	✓		5				✓	✓	✓			✓	✓	✓		✓		✓	✓		✓	✓	✓	
PIC18FXXQ10	28–40	128	3728	1024	$10^{(3)}$	✓		5				✓	✓	✓			✓		✓		✓					✓	✓		

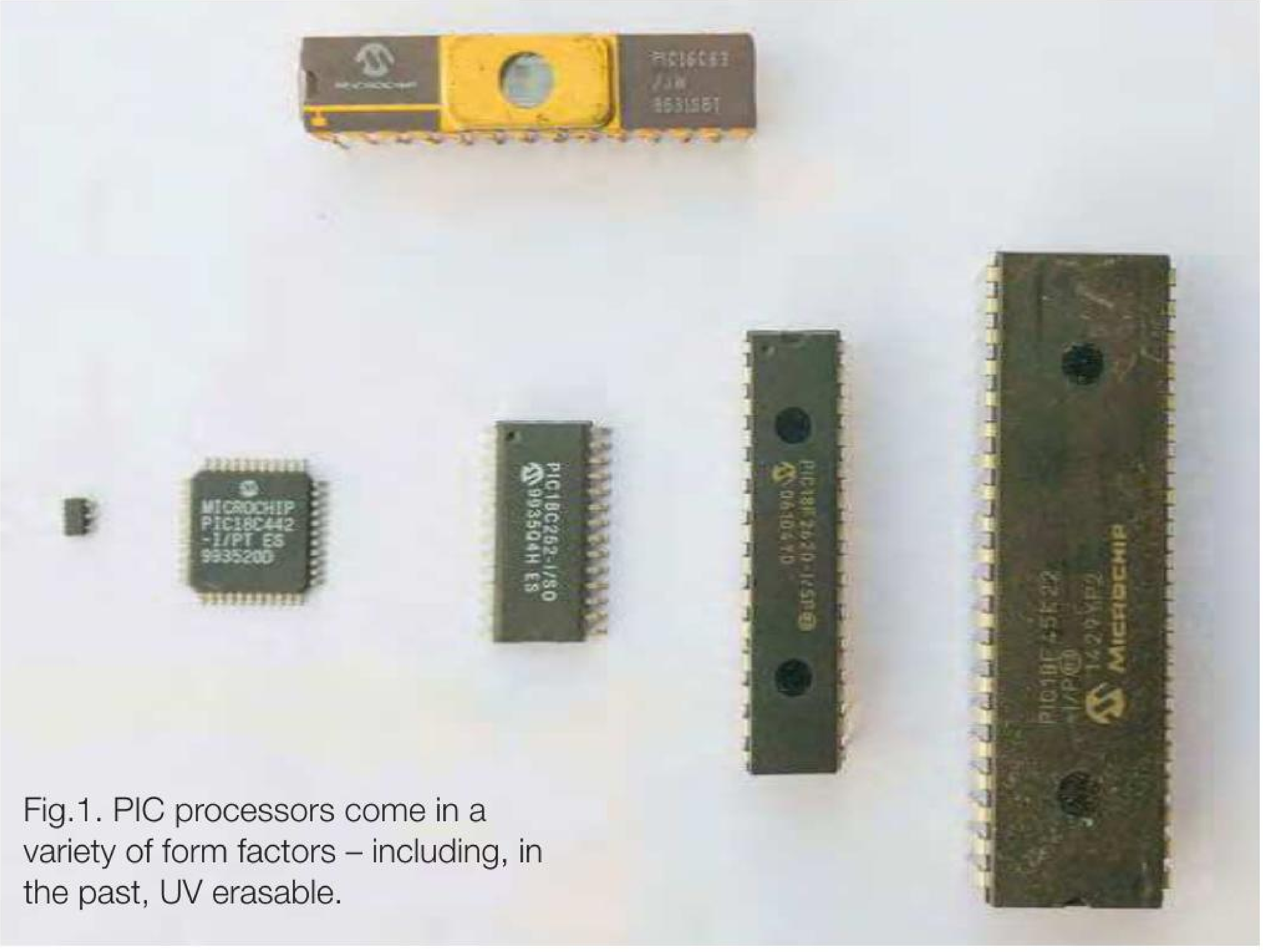


Fig.1. PIC processors come in a variety of form factors – including, in the past, UV erasable.

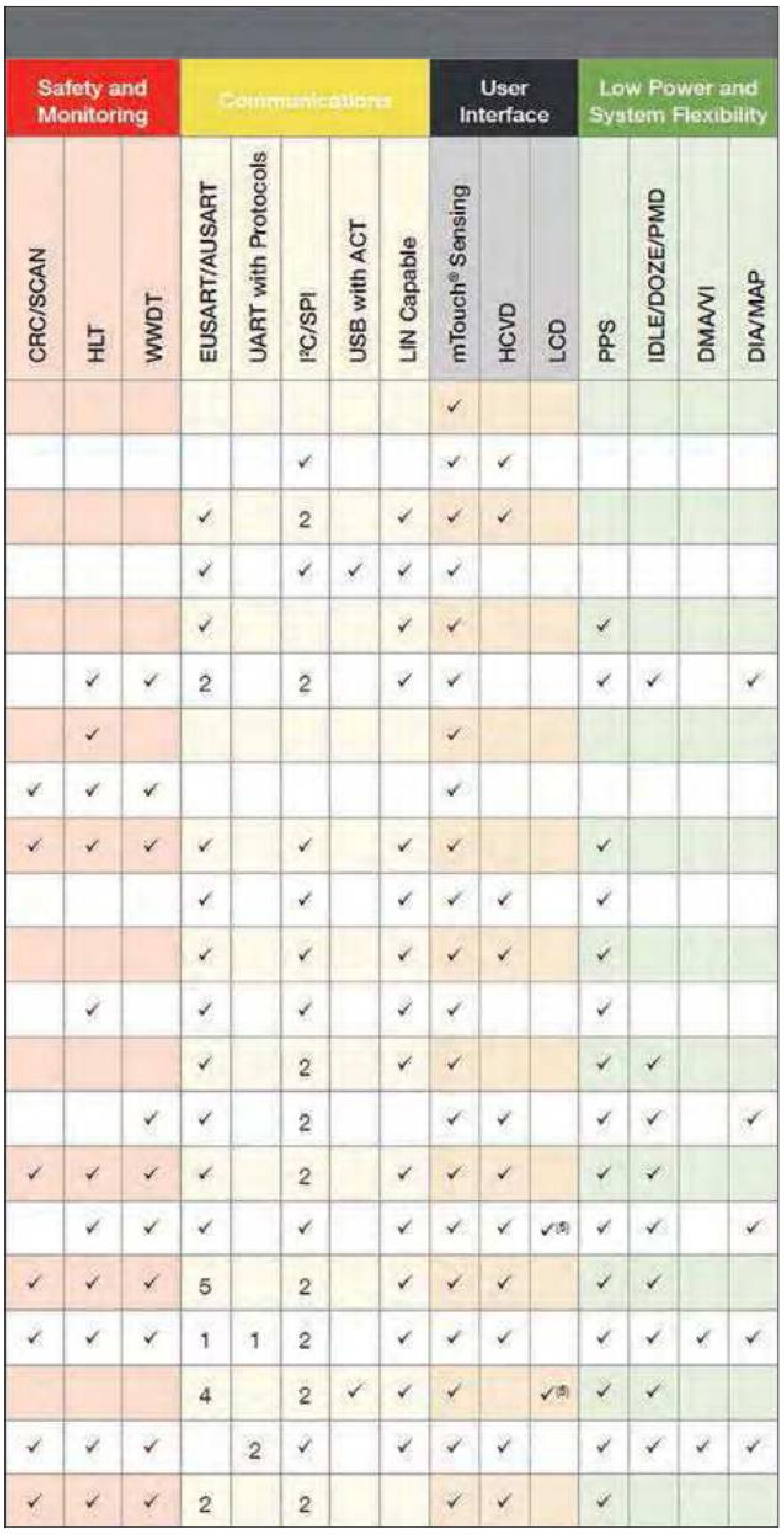
core, with the first four families being 8-bit processors, PIC24 and PIC33 are 16-bit; and the PIC32 is a 32-bit processor. These are slightly confusing names, so from the get-go, do not make the understandable mistake of thinking that PIC18 (or especially PIC16) PICs are anything other than 8-bit-based designs.

Each family of processors has a wide range of on-chip peripheral options, memory sizes and package types. You can see some examples of the package varieties in Fig.1, taken from the *PIC n' Mix* lab stock. That little collection includes a windowed UV-erasable PIC16C63, which was purchased in 1996!

The PIC10 and PIC12 families are low pin count (6 and 8 pins respectively) and are designed for very simple applications. Despite their minimal capabilities – a few bytes of RAM, and a few hundred bytes of code memory – these devices can still be programmed in a high-level language such as 'C'. The author used one in an industrial application recently.

The PIC16 family are more capable and have a much wider range of peripheral options and packages. Readers of the magazine will be familiar with the PIC16F877, a 40-pin device that has been a popular choice of many authors over the years.

The PIC18 family represents the peak of 8-bit processor performance and variety, with their key differentiator being larger memory availability, both SRAM and Flash. For commercial applications the PIC16 family is still relevant when low cost or simply continuity of an old design is relevant, but the PIC18 is our go-to family these days, especially when designing easy-to-assemble projects.



Safety and Monitoring			Communications					User Interface			Low Power and System Flexibility			
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			4		2	✓	✓	✓		✓(5)	✓	✓		
✓	✓	✓		2	✓		✓	✓	✓		✓	✓	✓	✓
✓	✓	✓	2		2			✓	✓		✓			

Fig.2 (left) PIC family features (Source: Microchip Technologies).

The PIC24 and PIC33 devices are 16-bit processors and intended for applications requiring DSP (digital signal processing) capabilities, such as motor or power supply control. They support more complex peripheral interfaces but are really better suited to specific use-cases; they are not an ideal choice for a general-purpose development platform.

We spoke to Microchip recently to enquire about the number of processor variants they had. Our local sales manager came back, saying he gave up counting after noting 17,000 variants. There are a lot to choose from!

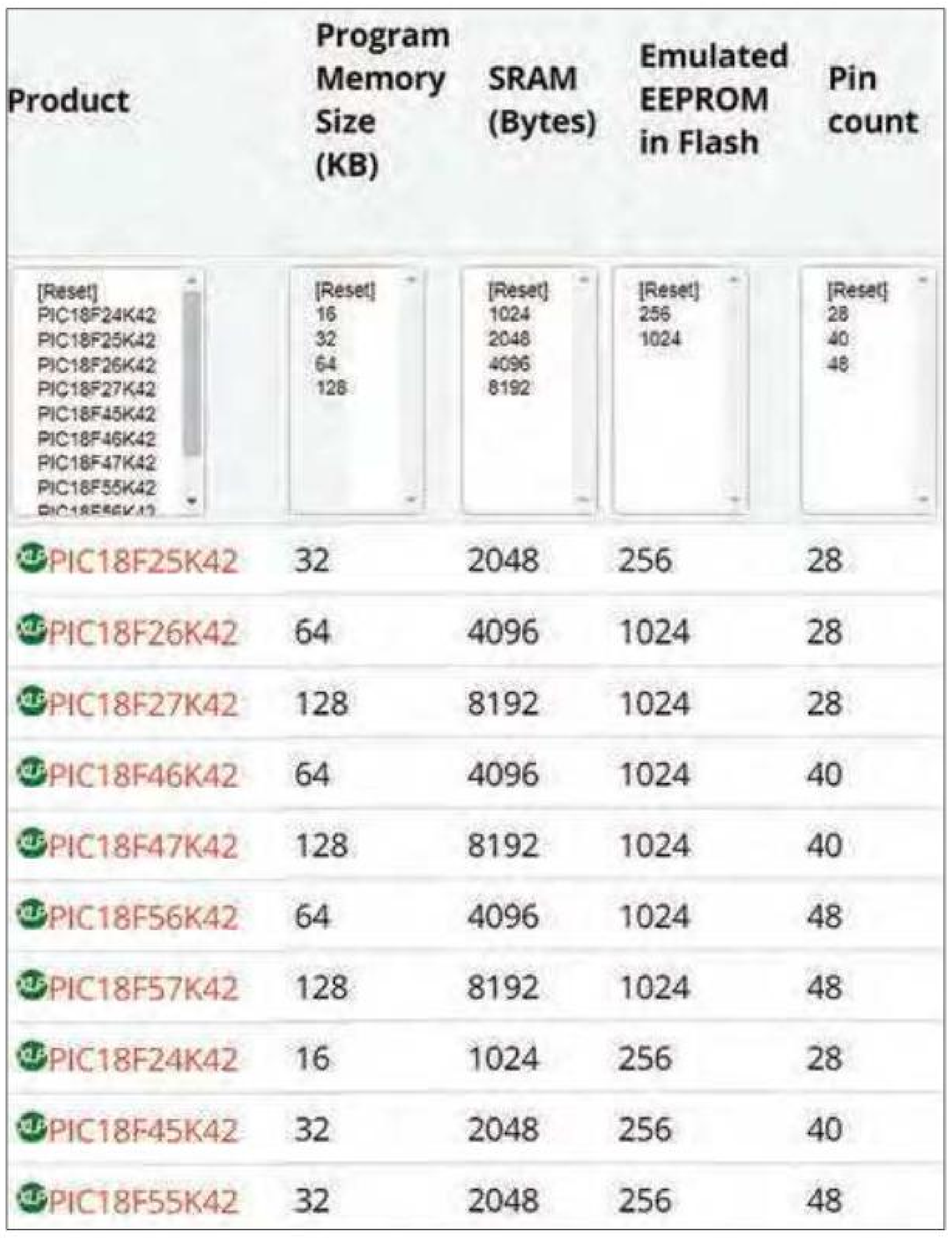
Fig.2 shows a selection table for the 8-bit processor families. It's interesting to see the distribution of available features across the range of devices; you wonder whether the decision of which peripherals to include is sometimes driven by large-volume customer requests.

For the purpose of this series of articles we wanted to introduce a highly flexible processor that could be used in many different projects, while still being easy to use. Perhaps not for absolute beginners, but for hobbyists keen to move on from Arduino-based projects, to learn more about the processor itself. With that in mind, we decided to use a PIC18 processor. Within this family there are lots of hobbyist-friendly parts (ie, in easy-to-use packages) which offer plenty of memory and a good selection of interesting peripherals. These parts are easy to source from the usual electronics distributors.

Meet the family

We liked the look of the PIC18(L)FxxK42 'sub-family' – 128KB of Flash, 8KB of RAM and a great range of peripherals. It also has the CLC (configurable logic cell) peripheral, which is a peripheral we have not yet played with, so this article series will give us the opportunity to explore it. The PIC18 family are optimised for use with the 'C' language, without being complex processors to set up. (The PIC32 for example is a very complicated device and requires a lot of engineering experience to get to grips with.) Writing software in assembly language is still possible, for those who really enjoy a challenge.

There are ten devices available within the PIC18(L)FxxK42 sub-family to choose from. We used the Microchip selection tool (**https://bit.ly/pe-jul20-pnm**) to compare the features, as shown in Fig.3. This is an abridged table; there are over 70 parameters to choose from when refining your search. With just ten parts available we quickly homed in on our preferred part, the PIC18F47K42 in a 40-pin DIP package. This device's feature list is impressive:



Product	Program Memory Size (KB)	SRAM (Bytes)	Emulated EEPROM in Flash	Pin count
[Reset] PIC18F24K42 PIC18F25K42 PIC18F26K42 PIC18F27K42 PIC18F45K42 PIC18F46K42 PIC18F47K42 PIC18F55K42 PIC18F56K42	[Reset] 16 32 64 128	[Reset] 1024 2048 4096 8192	[Reset] 256 1024	[Reset] 28 40 48
PIC18F25K42	32	2048	256	28
PIC18F26K42	64	4096	1024	28
PIC18F27K42	128	8192	1024	28
PIC18F46K42	64	4096	1024	40
PIC18F47K42	128	8192	1024	40
PIC18F56K42	64	4096	1024	48
PIC18F57K42	128	8192	1024	48
PIC18F24K42	16	1024	256	28
PIC18F45K42	32	2048	256	40
PIC18F55K42	32	2048	256	48

Fig.3 PIC18(L)FxxK42 family selection.

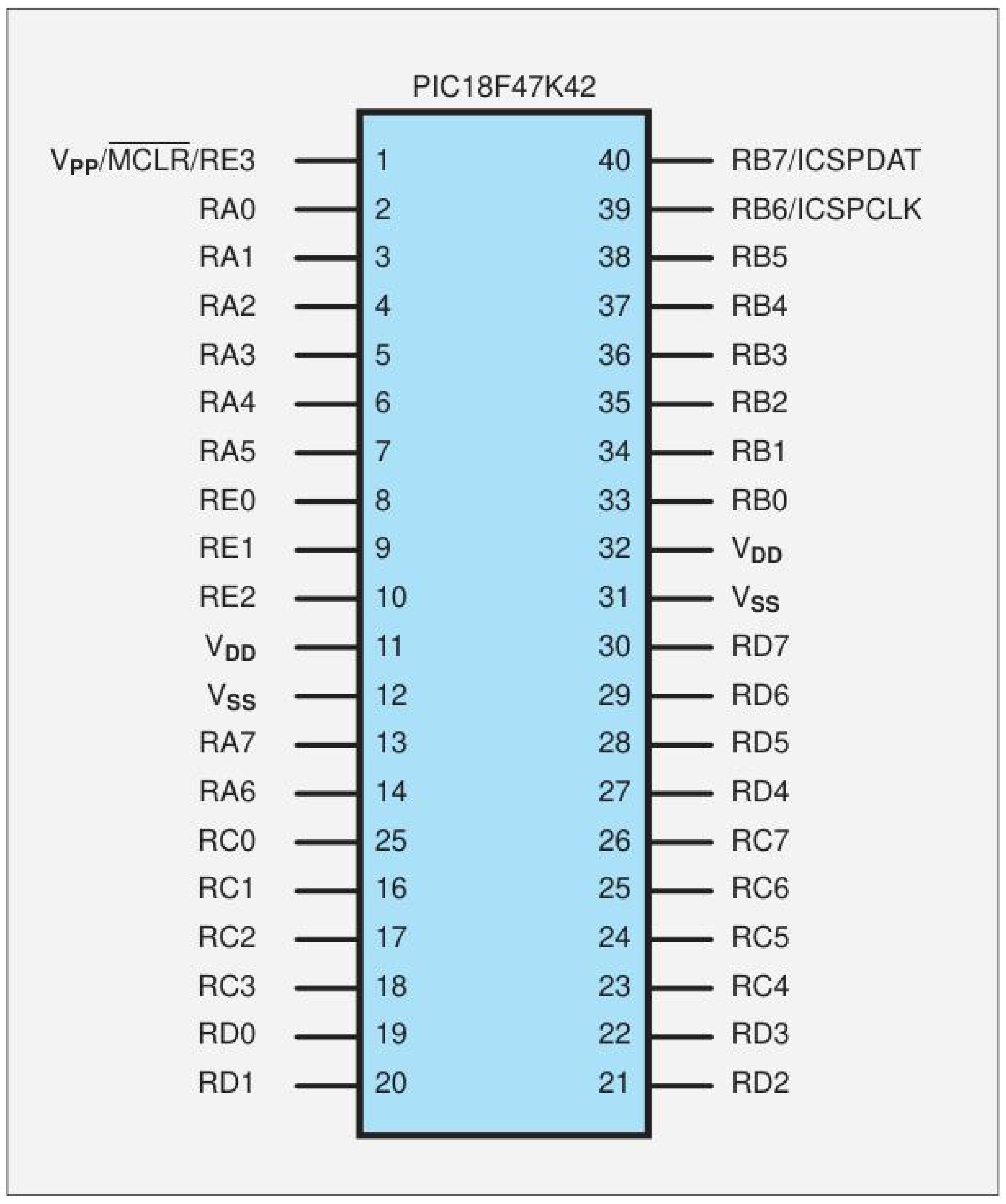


Fig.4 The PIC18F47K42 pinout.

- 128KB Flash
- 8KB SRAM
- 1KB EEPROM
- 35-channel 12-bit ADC
- 2 analogue comparators
- DAC (which can be connected to the comparators, that's useful)
- 4 PWMs
- 2 UARTs
- 2 I²C buses
- SPI bus
- Multiple timers
- 36 GPIO pins.

And that is just the key peripherals, there are a dozen other interesting features too – all that, for the price of a bottle of Coke.

There are some peripherals missing on this device that we would have liked to play with, such as I²S for high-quality audio output and a USB peripheral (although we will add USB interfacing on our development board) but we will pick those up in future articles. The pin-out of the IC can be seen in Fig.4, and the block diagram of the internals in Fig.5.

The device has two internal oscillators, a high-speed one to provide the 64MHz system clock, and a 31kHz low-frequency clock designed to provide operation of the device under very-low-current consumption. The high-frequency oscillator is factory calibrated and is accurate enough to provide high-speed UART communications – removing the need for any external crystals. The block diagram also shows the code access and data accesses are on different buses (the thick grey lines) – this processor is a Harvard Architecture CPU. Having the two buses separated enables the CPU to be more efficient, allowing, for example, the DMA peripheral to move data from, say, the UART into memory while the CPU is executing other tasks. It's like having a second processor in the chip – nice!

The processor also has a feature called PPS (Peripheral Pin Select) that allows most of the peripherals to be mapped to a GPIO pin of your choice – which can significantly simplify your PCB designs.

Take your PIC

So why would you want to build a microcontroller project rather than using something simple and off-the-shelf, like an Arduino or even a Raspberry Pi? Arduinos come in all shape and sizes and are very cheap. We are certainly not 'knocking' these platforms, they are very useful and very simple to use, but there are some really good reasons to go with a bottom-up custom design:

1. You will learn more about microcontrollers. The Arduino platform is excellent, but it abstracts the low-level details away, leaving you with more of a 'Lego assembly' process, so you learn less.
2. You may have size constraints. If you want to build something small or light, you can build exactly what is required, and no more.
3. You may have power constraints. Microcontrollers can operate down to a few microamps or less; an Arduino platform comes with extra features you do not need in the final product, like USB interfaces and power LEDs, which can increase this minimum current consumption a thousand fold.
4. Your design may be complicated. Arduino platforms do not have great debugging capabilities, which will make tracking down hard-to-reproduce software issues very difficult.
5. You may be designing an actual product. Microchip microcontrollers will always be available, even decades from now. If you design with an unusual Arduino development board, you may well find the manufacturer obsoleting the board with no notice – this is not uncommon.

Our development board is going to provide several on-board features for experimentation:

- A PC serial communications interface, using an on-board UART-to-USB converter chip, the MCP2221A.
- A header connector for the ESP-01 Wi-Fi interface.
- A header for an SD-Media card module.
- Three-pin headers for servomotor drive.
- A header for a colour touchscreen LCD.
- FET power switches for external device control.
- A PICkit 4 header for programming and debugging.
- Interfaces for I²C and SPI bus devices.
- Two configurable op-amps.
- Loads of analogue input and digital I/O headers.

One of the key questions we will have to answer along the way is whether we will support 5V or 3.3V external devices, or both. The design shall be, however, optimised for low-power operation, if desired. Our board will use through-hole parts as much as possible to minimise the soldering complexity.

PIC Internals

Let's go back to the processor itself and look at the key building blocks within the device.

CPU

The CPU is the key feature that distinguishes the different product families, and the PIC18 family is an 8-bit processor but has a 16-bit instruction size, allowing for many more instructions compared with the PIC16 or smaller devices. It can process most instructions in 62.5ns, allowing for up to 16 million instructions per second. There is a hardware multiply instruction too, along with low-power modes that can bring the processor down to an active current consumption of just a few microamps.

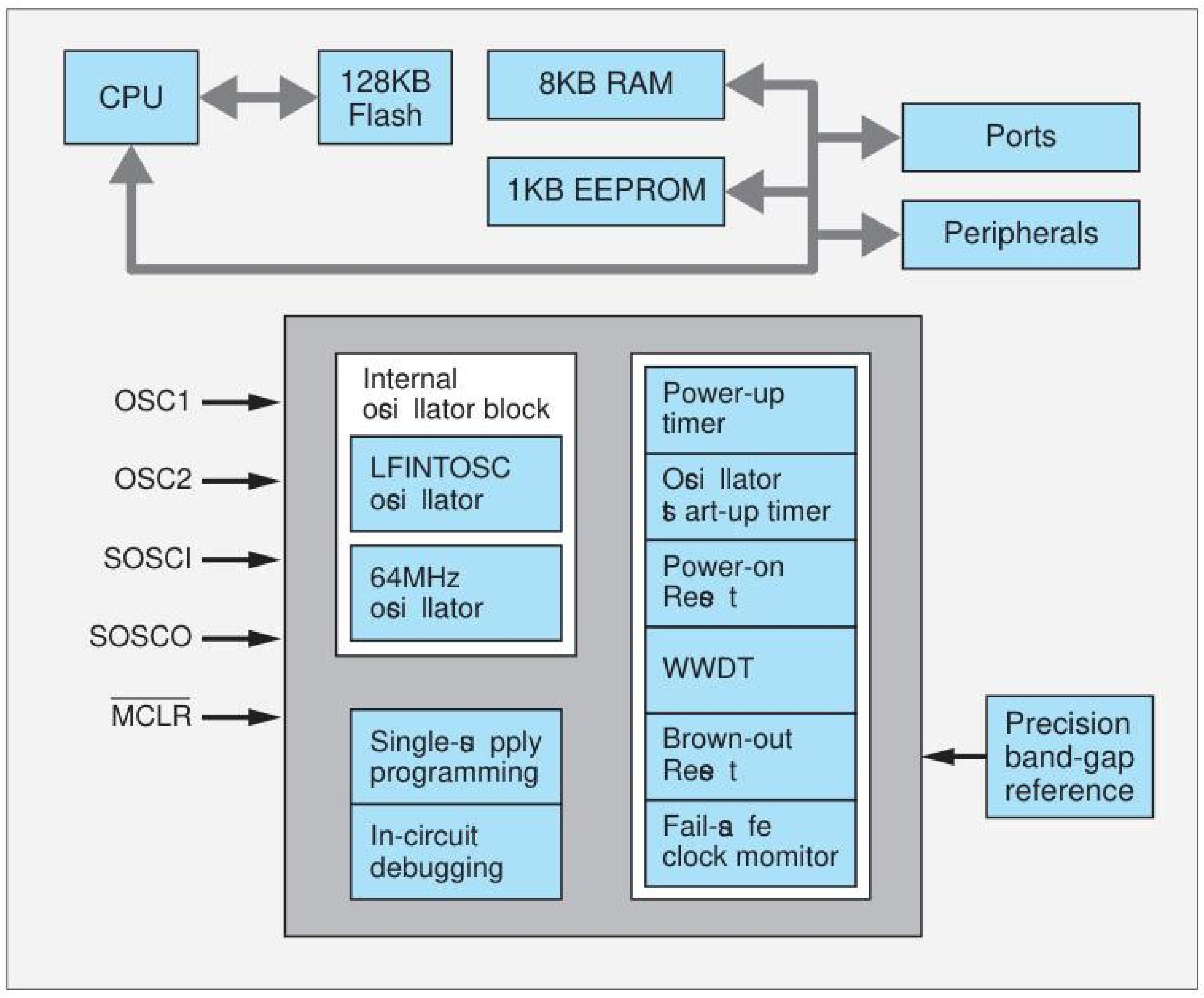


Fig.5. PIC18F47K42 block diagram.

Flash

128KB of non-volatile memory is available on chip. This memory is normally used for program storage, but it can also be used for fixed data or constants that needs to be preserved when power is removed. The memory is typically programmed through the debug interface using a PICKit 4 debugger/programmer, but the CPU can write to this memory too, allowing for software updates to be performed and controlled by the processor itself. With the addition of a Wi-Fi module, this means we can support remote firmware update – if we write the software to do it!

SRAM

8KB of SRAM is available on chip. This is typically used for program variables, and the data will be lost when power is removed. For a small, embedded project, 8KB is a huge amount of memory.

EEPROM

1KB of non-volatile EEPROM is available, again within the processor itself. EEPROM memory is more easily writeable than Flash memory, and is used for unique device configuration data, such as Wi-Fi credentials, or calibration data. This memory can be written via the debug interface or by the processor itself.

I²C

Two I²C buses are provided on the device. An I²C bus is a two-wire communication interface intended to provide a communication path between two or more devices, either on the same PCB or a short distance away, such as within an enclosure. Multiple ICs can be connected to a single bus, but the data speeds are low, below 1MHz typically. ICs such as temperature sensors, accelerometers and gyros typically use this interface.

SPI

A single SPI bus is provided on the device. The SPI bus is a three-wire interface, with a fourth wire used as a 'chip-select' to allow multiple devices to communicate on the same bus. The SPI interface runs at up to 16MHz and is used for high-speed interfaces, such as LCD displays or communication modules.

UART

Two UART interfaces are provided; the UART provides classic serial communication capabilities and can be used, in conjunction with an RS232 or RS485 interface IC, to provide wired communication over long distances. We will use one of these UARTs to communicate with a PC over a USB interface converter, and the other to communicate with the plug-in Wi-Fi module. The UARTs can, however, be re-mapped to other GPIO pins under software control.

GPIO

36 GPIO (general-purpose input/output) pins are available on the 40-pin package we have selected. However, not all of these pins are free for general-purpose use because some GPIO pins are required for any of the other peripheral features we use. These are digital signals and will output 0V or 3.3V under program control.

ADC

35 of the GPIO pins can also be configured as analogue input signals to the single ADC converter present on the chip. The ADC has a resolution of 12 bits, which means it can resolve input signal voltage changes down to 1mV, at speeds of up to 1MHz sample rates. We will make a number of the ADC channels available via headers and connect some configurable op amps to allow easy connection of microphones or other audio sources. ADCs are used for a variety of uses (hence, the large number of input channels offered.) We will use one channel to measure the input power supply voltage, to enable the monitoring of battery level.

Next time

In our next article we will look at the software tools available for working with the processor. These include MPLAB-X, an integrated development environment, the XC8 'C' language compiler and the MCC Code Configurator tool, which provides 'ready-to-go' example code for the different peripherals within the processor.

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Max's Cool Beans

By Max the Magnificent

Flashing LEDs and drooling engineers – Part 5

In my previous column (PE, June 2020), we considered a traditional tricolour LED containing three RGB LEDs with a common cathode. For the purpose of these discussions, we will refer to these as 'sub-LEDs' to remind ourselves that they are inside the main device. When I was younger, brighter-eyed, and bushier-tailed, I remember how I used to think these devices were as 'cool as cucumber.' To be honest, however, I've grown a little jaded over the years to the extent that I was a tad disappointed with the result.

First, each such LED requires three of the digital input/output (I/O) pins on your microcontroller unit (MCU) to drive it. Second, if you wish to access more than the eight basic colours provided by turning the three sub-LEDs on and off – red, green, blue, yellow (red + green), cyan (green + blue), hot pink (red + blue), white (all on), and black (all off) – then these pins have to support pulse-width modulation (PWM) as described in *Part 1* of this mini-series (*PE*, March 2020). And third, I really wasn't impressed with the final effect.

Nifty NeoPixels

Now turn that frown upside down into a smile, because a different sort of tricolour LED that never fails to delight is the WS2812, which is also known as a 'NeoPixel' (a term originally coined by the folks at Adafruit). This little beauty is about 5 × 5mm square and 2mm thick (Fig.1). In addition to three ultra-bright RGB sub-LEDs, the WS2812 also contains a tiny WS2811 controller chip that contains three 8-bit PWMs – one for each of the sub-LEDs – and supports a simple serial communications protocol.

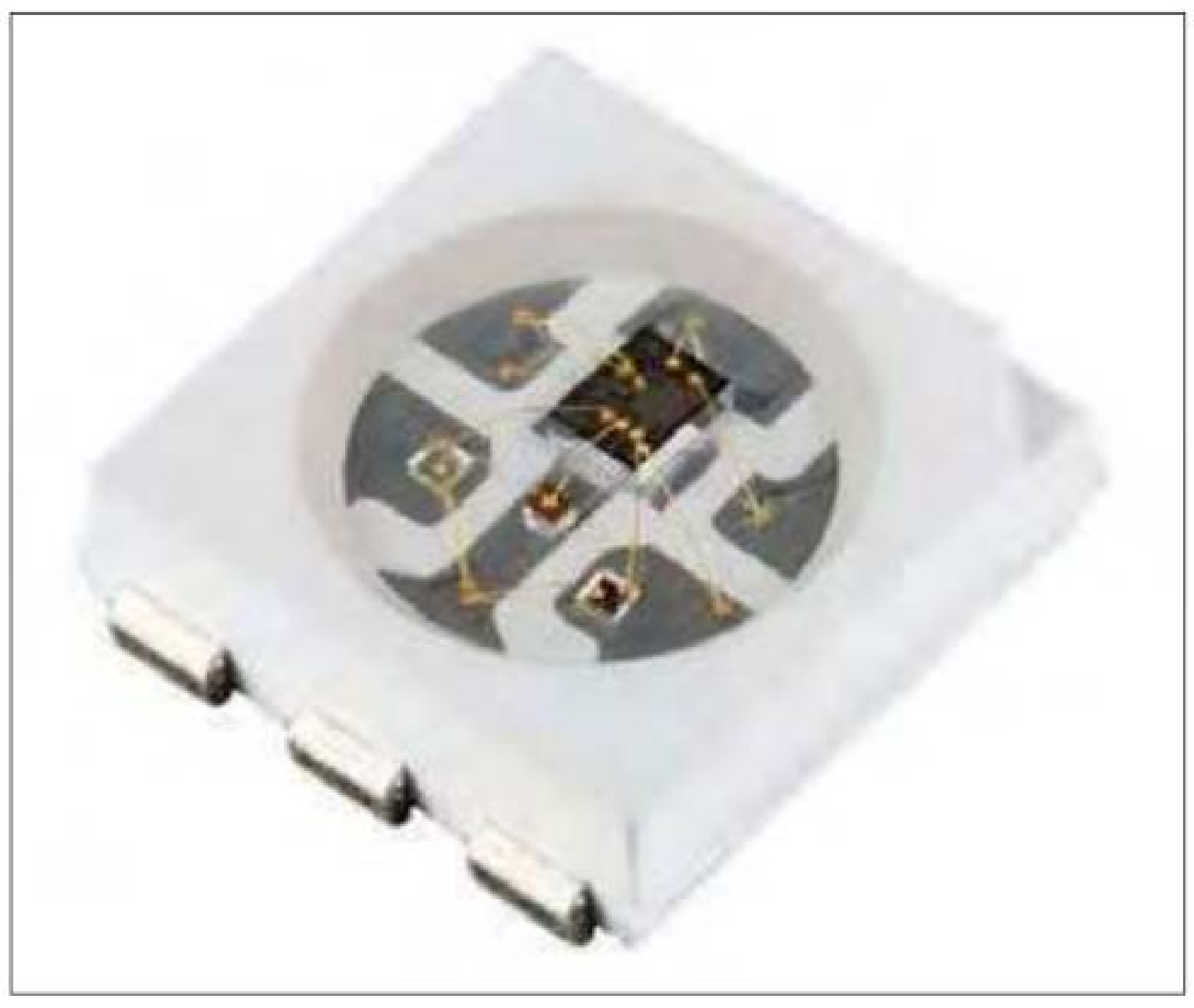

Fig.1. WS2812 aka 'NeoPixel'.

Each NeoPixel has four pins (some come in 6-pin packages, but only four of the pins do anything): 0V, 5V, Data-In, and Data-Out, where the Data-Out from one NeoPixel can drive the Data-In of another. This allows long strings of NeoPixels to be daisy-chained together and for the entire chain to be controlled by a single digital MCU output.

NeoPixels are available in a variety of packaging options, including raw chips (**https://bit.ly/2SOBe8b**), individual Flora breakout boards (**https://bit.ly/3ck1ZZS**), and traditional 8mm through-hole packages (**https://bit.ly/3bkJbs5**). In the case of the Floras, I like to buy them in sheets of 20 (**https://bit.ly/2LdFRVq**).

You can also get these little scamps in bars, rings, jewels and arrays (just go to **Adafruit.com**, search for 'NeoPixel,' and wend your way through their 28 glorious pages of NeoPixel products). For the purpose of the project I'll be discussing later in this column, I'm using a 5m strip containing 30 NeoPixels per meter (**https://bit.ly/2SNHTzL**). There are strips with 60 and 144 NeoPixels per meter, but I will be chopping my strip into 144 individual segments. From experience, I know that chopping the 30-per-meter strips leaves me with larger copper pads for soldering than chopping the 60 or 144-per-meter strips. Actually, for this particular project, I would have preferred to use Floras as discussed above, but the strips give me 30 NeoPixels for US$17, while the Flora sheets give only 20 NeoPixels for US$35. Since I require 144 NeoPixels for this project, chopping strips provides a much cheaper option.

Nitty gritty details

Purely for the sake of giving us something to talk about, let's assume we wish to drive a strip of NeoPixels (Fig.2). There are a couple of points to note on the physical implementation front. Theoretically, each NeoPixel can consume as much as 60mA if all three sub-LEDs are fully on (they are rated at 20mA each). In practice, I've only ever measured them at 45mA fully on, so this is the value I go by.

Now, working with only a handful of NeoPixels is one thing, but if you are driving a large number you have to start paying attention to how much current you are consuming. In the case of the project we will be discussing in a moment, my worst-case current consumption would be 50mA for an Arduino and (144 × 45mA) for my NeoPixels if I were to drive them all full on to give a brilliant white. This gives us a grand total of 6,530mA, which means I'll need a power supply that can provide at least 7A to give me some head room. In practice, of course, I will probably be lighting only a subset of the NeoPixels, and I'll typically be lighting those with only one or two of the sub-LEDs, but it's always best to design for the worst-case scenario.

Personally, I generally use the same supply to power my MCU and my NeoPixels, but different folks do things in different ways. If you decide to use your USB cable to power your MCU and a separate supply to power your NeoPixels, for example, then it's *very important* to ensure that both the MCU and NeoPixel 0V (GND) signals are connected together.

It's also a good idea to add a large electrolytic capacitor (1,000µF, 6.3V or higher) across the 0V (GND) and 5V terminals of your power supply. If you are using raw WS2812s or NeoPixels in through-hole packages, then it's important to include a 100nF ceramic capacitor between the 0V and 5V terminals of each package. This is another good reason for using Adafruit's Floras or rings or strips, because they already have these capacitors in place.

Furthermore, it's important to include a serial resistor as close as possible to the first element in the NeoPixel chain (Adafruit's

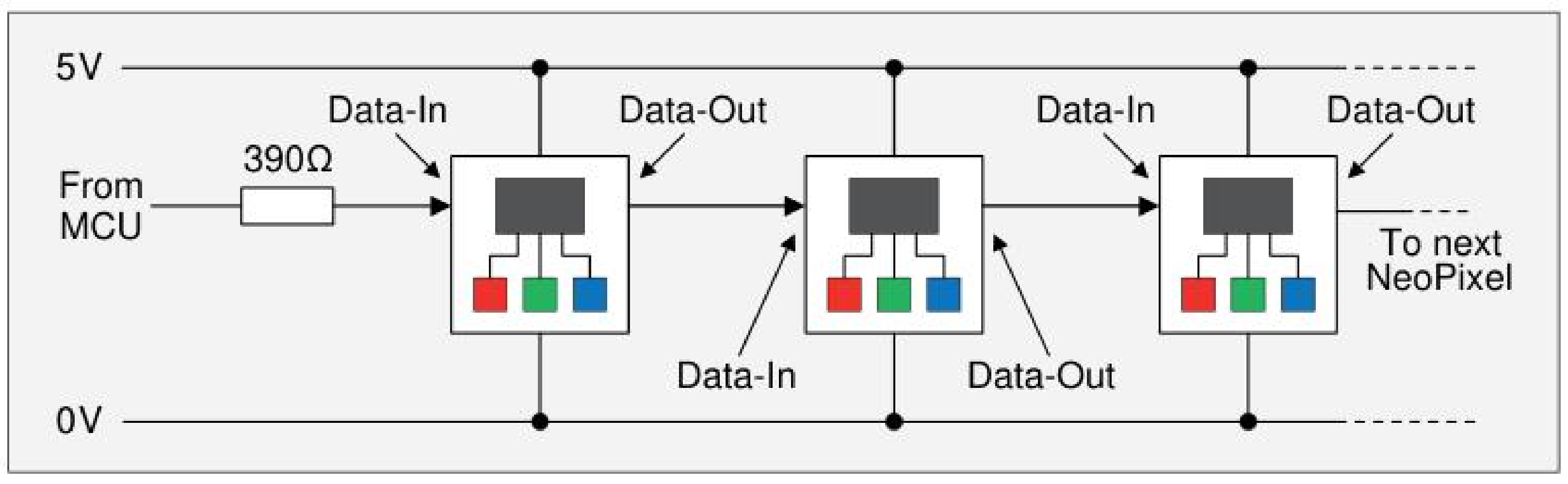

Fig.2. Driving a chain of NeoPixels.

NeoPixel rings already have such a resistor installed). When I first started using NeoPixel strips, every now and then the first one in the chain would die on me. When I used an oscilloscope to look at the Data-In signal coming from my Arduino Uno, I saw that the edge rate was so fast it was overshooting the 5V and undershooting the 0V. After a bit of dabbling around, I determined that a 390Ω resistor dampened things down nicely and I haven't had any problems since. Having said this, I should note that, in their *NeoPixel Uberguide* (**https://bit.ly/2SRl4eu**), which is well worth perusing and pondering, the folks from Adafruit recommend using a 470Ω resistor. I've also seen other people offering different suggestions, but long ago I purchased a couple of hundred 390Ω resistors for this very purpose, so that's what I'm going to use by golly!

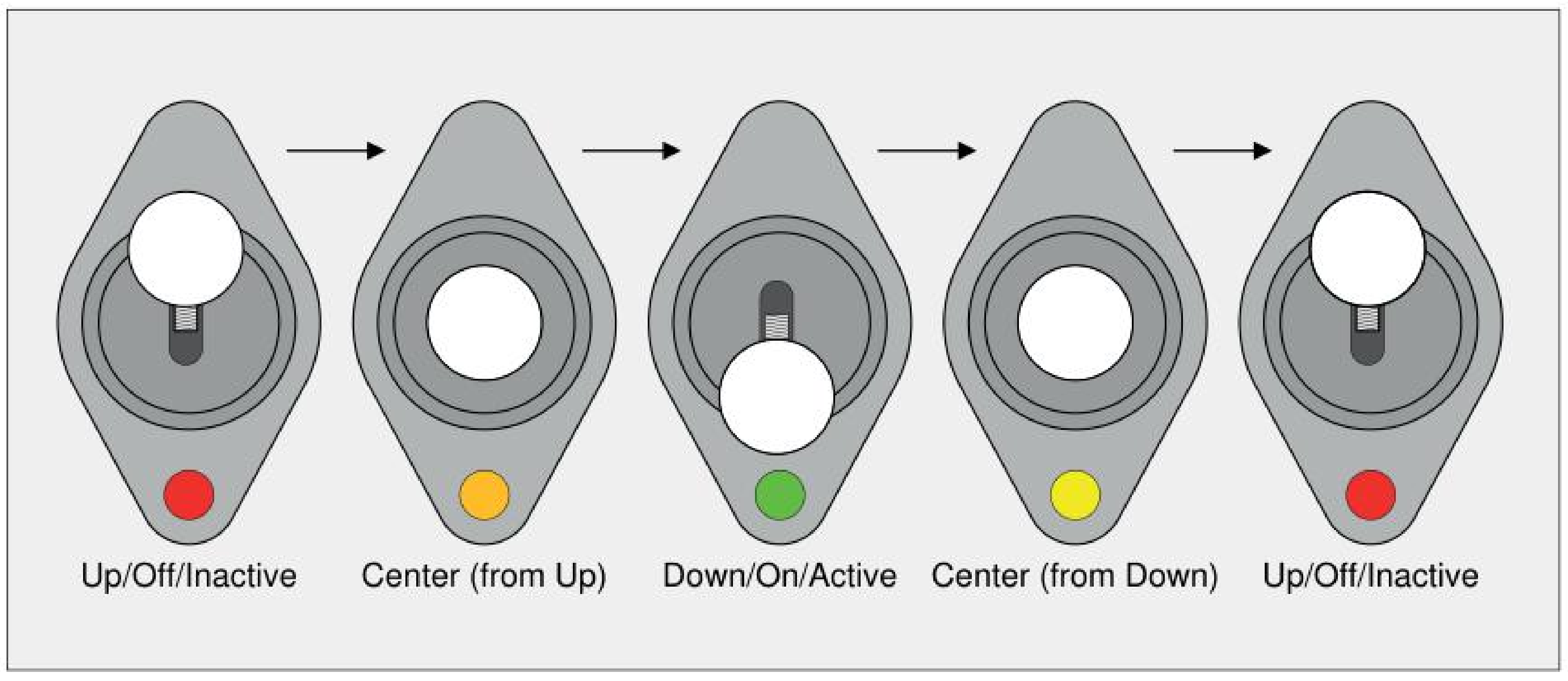

Fig.3. Using a tricolour NeoPixel with an SPCO switch and with two colours for the centre position.

Luscious libraries

There are a number of libraries floating around that you can use to drive your NeoPixels. If I'm using an Arduino or related MCU, I almost invariably use the library from Adafruit (**https://bit.ly/2LdPxPK**). Another easy-to-use Arduino library for programming NeoPixels (and other devices) that many of my friends recommend is the FastLED Animation Library (**http://fastled.io/**). Alternatively, if I'm using a Teensy MCU from **PJRC.com**, then I will use their OctoWS2811 Library (**https://bit.ly/2YLER2I**) in conjunction with the OctoWS2811 Adaptor (**https://bit.ly/2SNyJmJ**).

In the case of the Adafruit library, you start by instantiating your string of NeoPixels, as part of which you specify how many pixels there will be in the chain and which of the Arduino's pins you wish to drive them. For each of your NeoPixels, the library will reserve three bytes in your Arduino's SRAM, which means an Arduino Uno with its 2KB of SRAM, for example, is limited to driving a maximum of around 500 NeoPixels, while leaving 512 bytes of SRAM free for other things.

Let's suppose we've instantiated a string of 10 NeoPixels, which will be numbered 0 to 9, and we've imaginatively called this string `MyNeos`. Now let's suppose that we use a statement like `MyNeos.setPixelColor(i,COLOR_HOT_PINK)`, where `i` is the number of the NeoPixel we wish to change, and `COLOR_HOT_PINK` is a 24-bit hexadecimal value representing the RGB components of our desired colour. It's important to note that this doesn't actually change the value of the NeoPixel in the string; instead, it changes the value in the reserved area of the Arduino's SRAM. It's only when you use the command `MyNeos.show()` that all of the values in memory are uploaded into the physical string. Don't worry, we'll be seeing simple examples of all of these things in the programs we create later.

Bits and bytes

It just struck me that there's one thing that can prove to be confusing if you are new to using NeoPixels – the fact that there are two ways for us to specify the colour we wish to use. Let's start by reminding ourselves that each NeoPixel contains red, green, and blue sub-LEDs. Also, it contains three 8-bit PWM functions, one for each of the sub-LEDs. This means that we can assign each sub-LED a value ranging from 0 to 255.

Suppose we wanted to set the seventh NeoPixel in the chain to a colour we might call 'electric violet' (remember that this pixel will actually be number 6 because we start counting at 0). Let's further suppose that, to achieve this colour, we want the red component to be 128, the green component to be 0, and the blue component to be 255. In this case, the creators of Adafruit's NeoPixel library have implemented things in such a way that we can use a statement like: `MyNeos.setPixelColor(6,128,0,255)`.

However, the cunning rascals have also implemented things in such a way that we can specify the combined RGB components as a single 24-bit value. It's best to use hexadecimal for this sort of thing, so we could achieve our electric violet colour using: `MyNeos.setPixelColor(6,0x8000FF)`, where `0x80` equates to `128` in decimal, `0x00` equates to `0` in decimal, and `0xFF` equates to `255` in decimal.

In many cases it is preferable to use this 24-bit value approach, because it lets us do things like pre-defining a colour using something like `#define COLOR_ELECTRIC_VIOLET 0x8000FFU`, where the `U` is used to indicate that this is an unsigned value. The use of the `U` (or `u`) is optional – the compiler can usually figure things out for itself – but it rarely hurts to give it the occasional hint, and it makes your intent clearer to someone else reading your code. Now, we could use `MyNeos.setPixelColor(6,COLOR_ELECTRIC_VIOLET)` in our program. If you download the sketches discussed later in this column, you'll see this is just what we did.

You turn me on

Before we progress to my new project, we first need to tidy things up with regard to our earlier switch experiments. Using a similar setup to the one discussed in my previous column, I mounted a single NeoPixel Flora on a breadboard and I wrote a little sketch to control it using a single-pole, centre-off (SPCO) switch.

As with the standard tricolour LED in my previous column, we'll use red to indicate when the switch is Off/Inactive, green to indicate when the switch is On/Active, and either orange or yellow when the switch is in its centre position to provide an indication as to its previous state (Fig.3). You can download a sketch (file **CB-Jul20-01.txt** – available on the July 2020 page of the *PE* website) and watch a video (**https://bit.ly/3cyCyUF**) to see all of this in action.

A brace of balls

And thus we arrive at my new hobby project. As I mentioned in my previous column, I decided to build a magnificent matrix based on ping pong balls illuminated by NeoPixels – something like the 'Video Wall' you can see on YouTube (**https://bit.ly/3aG1itl**).

I also decided that my first pass would be a small, 12 × 12 = 144 ping-pong prototype. It turns out that you can buy a bag of 144 ping pong balls for only $11 in the US, but I knew I'd need some spares, so I purchased two bags, giving me 288 ping pong balls in all.

Of course, I was immediately tempted to 'go bigger and better' – say a 15 × 15 = 225 array – but I'd already ordered five meters of 30 pixels per meter NeoPixel strip from Adafruit (**https://bit.ly/3dOa5v4**), which will give me 150 NeoPixels, so I decided to stick with the original plan. Thank goodness I did, because everything is requiring significantly more effort and taking much longer than I'd originally planned.

I started by considering how I was going to attach the segments of NeoPixel strip to my ping pong balls. I was working with a

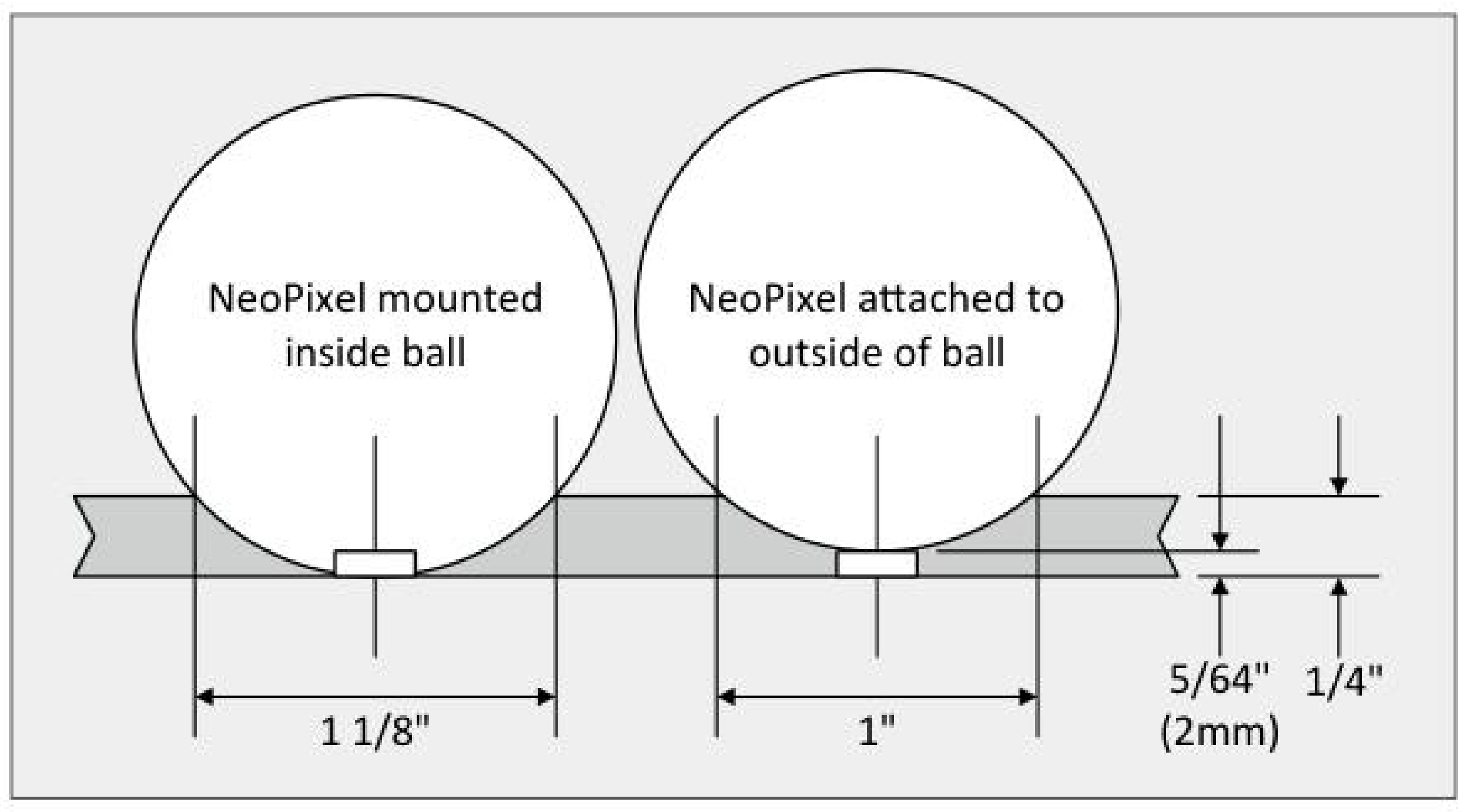
NeoPixel mounted inside ball
NeoPixel attached to outside of ball
1 1/8"
1"
5/64" (2mm)
1/4"

Fig.4. NeoPixel attachment alternatives (theoretical).

nice piece of 6mm (1/4-inch) thick plywood. I want the strips themselves to be flush with the surface of the wood. Knowing that the NeoPixels protrude from the surface of the strips by 2mm (5/64-inch), there are two obvious alternatives (Fig.4).

The first option is to cut a hole into the ping pong ball and mount the NeoPixel inside the ball. In this case, since the balls are 38mm (1 1/2-inch) in diameter (I'm also allowing 1.5mm (1/16-inch) between balls for 'wriggle room'), the hole I drill through the board would need to be 28.6mm (1 1/8-inch) in diameter so as to have the base of the ball flush with the bottom of the board. The second option would be to attach the NeoPixel to the outside of the ball. In this case, the hole I drill through the board would only need to be 25mm (1-inch) in diameter.

To be honest, I didn't think there would be much difference between these two schemes with regard to the way they looked, but I decided to build a prototype using a piece of cardboard and a brace of balls. I created a little video showing the same sequence of colours being displayed in both balls (**https://bit.ly/2WZN6pq**), and you can download the sketch I used (file **CB-Jul20-02.txt** – available on the July 2020 page of the *PE* website).

I told myself they looked the same, but I also asked my wife (Gina the Gorgeous) and my 25-year-old son (Joseph the Commonsense Challenged), and they both said that one looked better (smoother) and brighter than the other. Although they look the same in Fig.5, there really is a difference when you are looking at them in the real world. Of course, the better option was the one that required me to cut 10mm (3/8-inch) holes in 144 ping pong balls. 'Oh dear,' I said to myself (or words to that effect).

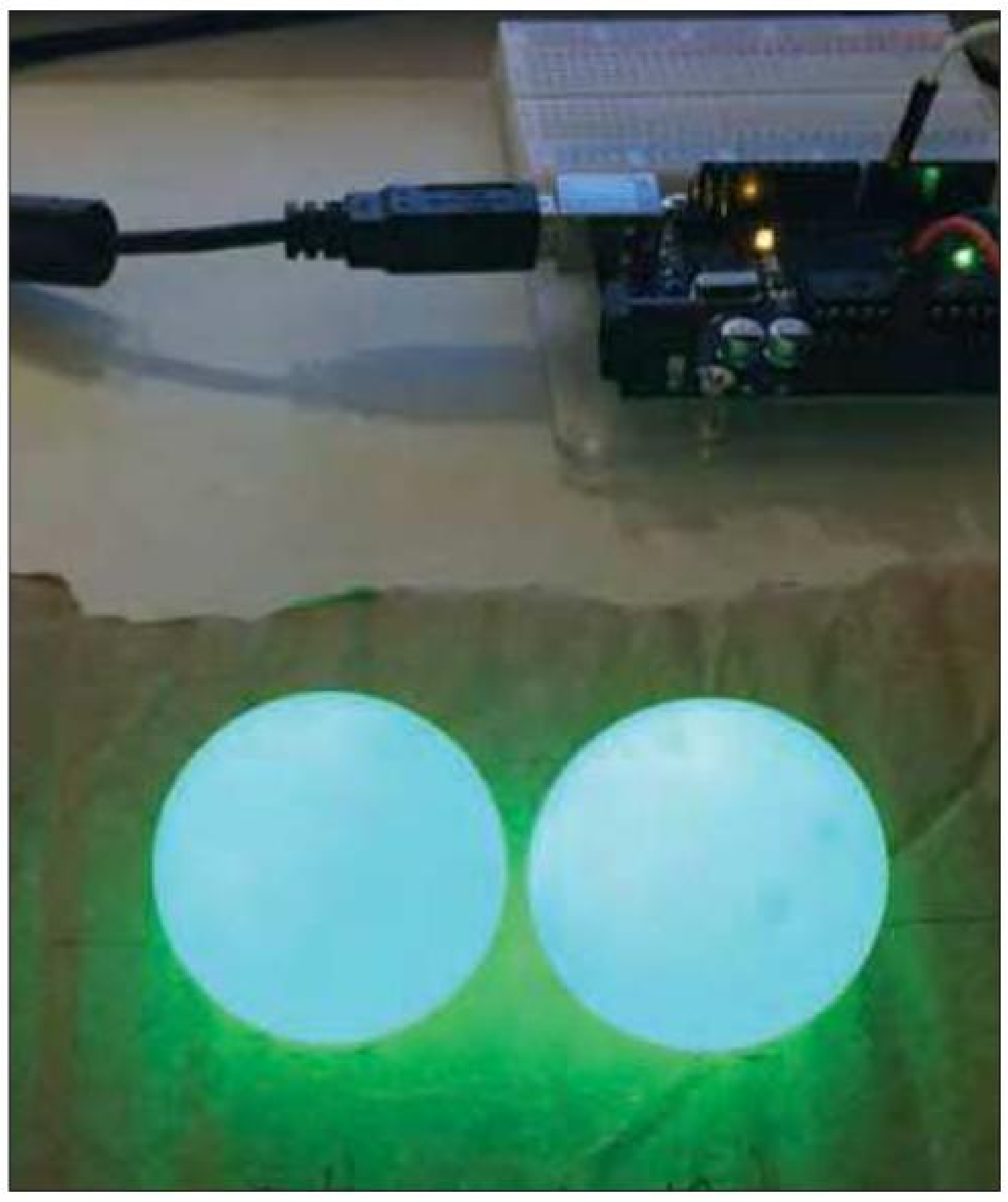

Fig.5. NeoPixel attachment alternatives (prototype).

But then I looked in my tool chest. Wouldn't you know it – the largest drill I had was 25mm (1-inch) diameter. 'Oh well,' I said to myself, 'the fates have made the decision for me, and – after all – the difference between the two schemes is really very slight.'

So, I went away and drilled my 144 × 25mm (1-inch) holes, sanded everything down, and painted the board black. When I'd finished, I took one ping pong ball and popped it into a hole. What? The bottom of the ball was flush with the lower surface of the board! How could this be?

It turned out that what I'd assumed to be a 6mm (1/4-inch) thick board when I'd seen it lying around in the garage was in fact only 5mm (3/16-inch) thick. So now I was back to having to cut the 10mm (3/8-inch) holes in my 144 ping pong balls. Actually, if the truth be told, I wasn't too dismayed, because knowing I'd opted for the easier, but lower-quality option had been niggling away at the back of my mind.

Building the board

I'm sure that, like me, over the years you've spent far more time than you'd care to remember on the frustrating task of drilling holes in ping pong balls. This time I came up with something different. First, I took a ball and held it up to the light to determine where the two hemispheres were joined, then I used a permanent marker to make a dot in the centre of one of the hemispheres (I don't want the join line to show). Next, I used a stencil to mark the 10mm (3/8-inch) circles centred on the dot. Finally, I used some small, sharp, curved nail scissors to puncture a small hole in the centre of the circle and carefully cut the ping-pong material away. I then repeated this process 143 more times (that's one long evening I'm never going to see again).

The next step was to attach the ping pong balls to the wooden sheet. I won't bore you with the problems I experienced aligning the balls and the jig I had to create. Suffice it to say that, if I ever build a wall-sized ping-pong-ball display, I will do so using 8 × 8 sub-arrays. So, let's skip the gnashing of teeth and rending of garb, and jump forward to the part where I say, 'As always, my hot glue gun proved to be a faithful friend.'

To be honest, I think the final result looks rather spiffy (Fig.6). I had hoped to have everything up and running in time for this column, but it was not to be. I still have to attach the 144 segments of NeoPixel strip, and then solder everything together (144 × 3 = 432 soldered connections – plus change), so we won't be able to see this little beauty in action until my next column.

The Seeeduino XIAO

In the past, I would have been tempted to use an 8-bit Arduino Nano for this project on the basis that it's relatively small and unobtrusive (**https://bit.ly/2LfK2jy**). On the other hand, the Nano has only a 16MHz clock, 32KB of Flash memory, and 2KB of SRAM, all of which is a tad limiting.

But then the fates came into play once again, because the folks at Seeed Studio told me about their Seeeduino XIAO (**https://bit.ly/3ckK31c**) and they even sent me one to play with. Costing only US$4.90 and being the size of a small postage stamp (Fig.7), this little beauty boasts a 32-bit Arm Cortex-M0+ processor running at 48MHz with 256KB of Flash memory and 32KB of SRAM. One thing to note is that the programming connector

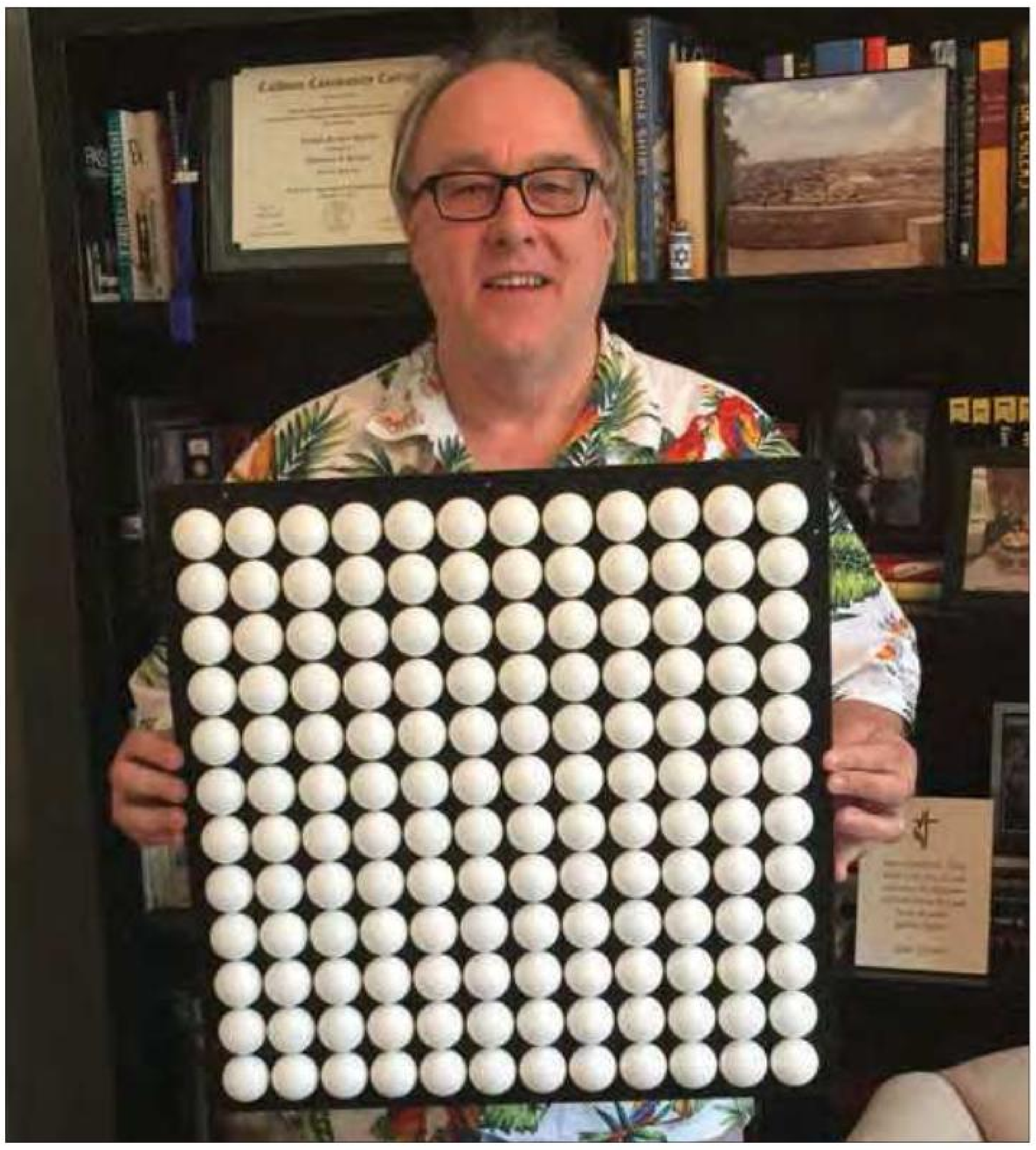

Fig.6. I'm convinced this is the best ping-pong-ball array on our street.

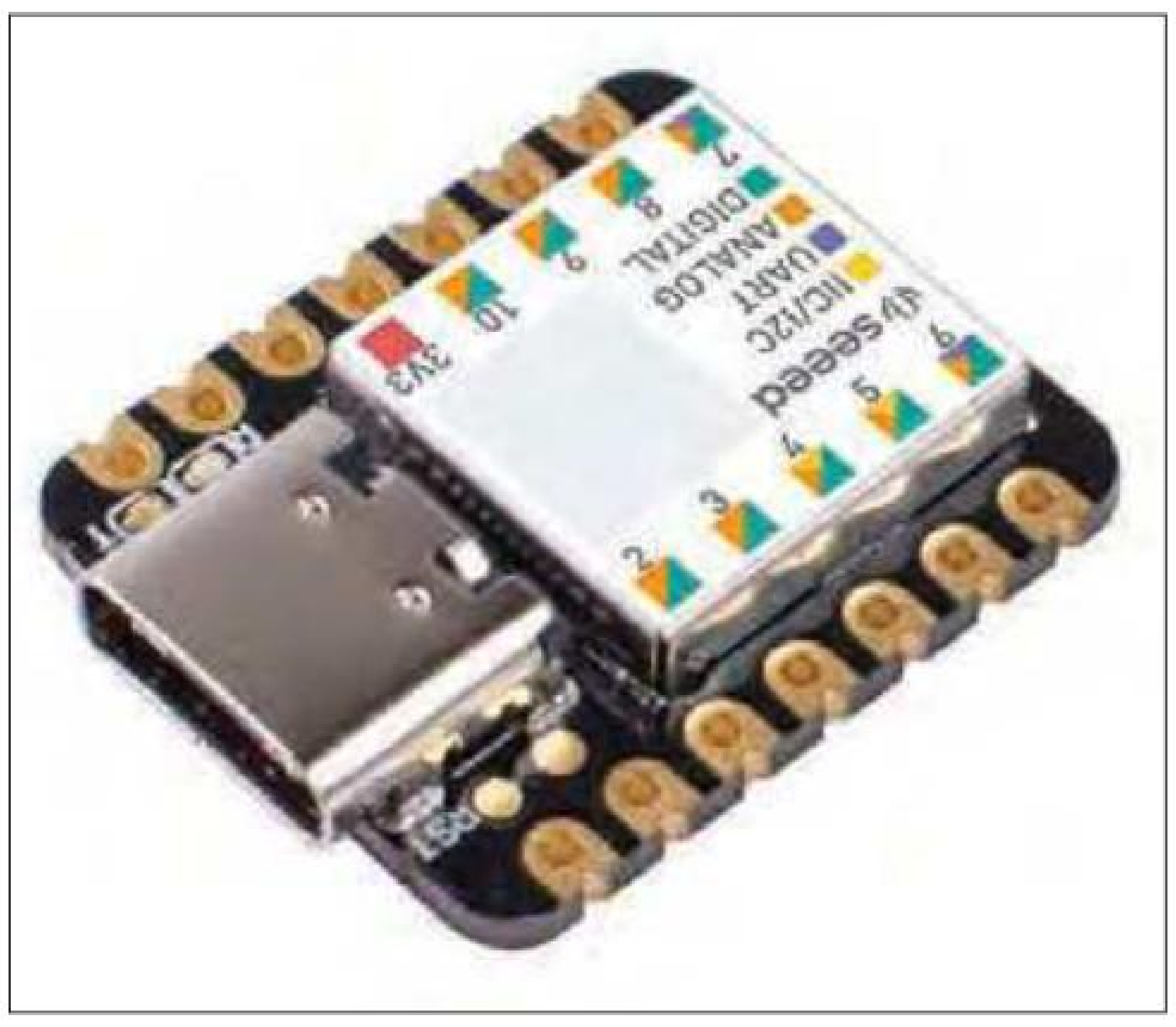

Fig.7. The Seeeduino: my new best friend.

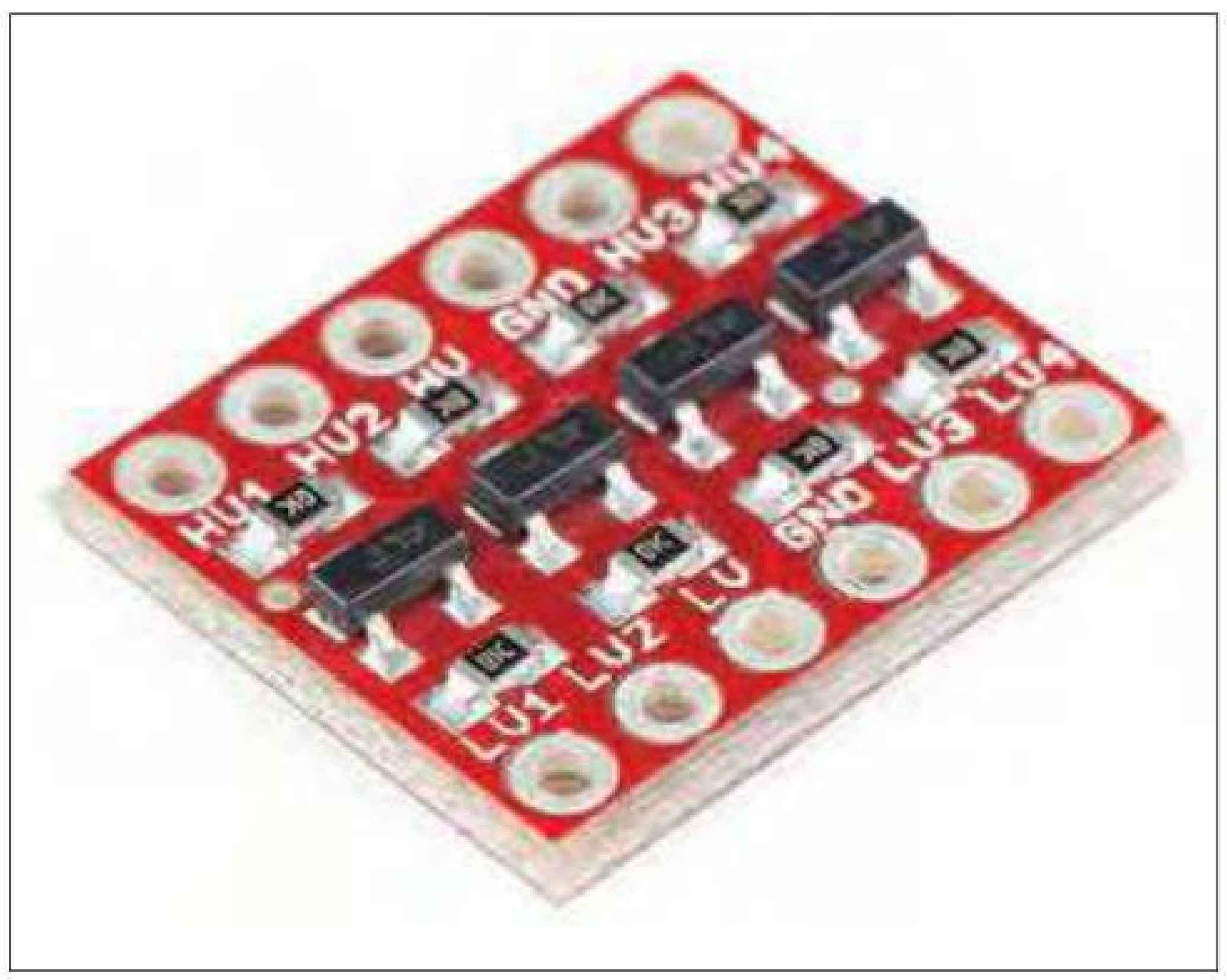

Fig.8. SparkFun's 4-bit bi-directional logic-level converter.

is USB Type-C, which means you're going to need a USB-A to USB Type-C cable.

The Seeeduino XIAO has 11 digital/analogue pins, 10 of which support PWM and one of which can provide a true digital-to-analogue converter (DAC) output. These pins can also be used to support a UART interface, an SPI interface, and an I²C interface. Apart from anything else, this little beauty would be great for implementing wearable light effects. I think it's safe to say that the Seeeduino XIAO is going to be making appearances in many of my future projects.

Keeping things level

On the bright side, the Seeeduino XIAO can be powered from the same 5V supply I use for my NeoPixels. However, there is a small fly in the soup or a large elephant in the room (I'm feeling in a generous mood, so I'll let you employ the metaphor of your choosing). The Seeeduino XIAO's I/O pins use a 3.3V interface, but my NeoPixels require 5V data signals, so we need some way to convert between the two.

In the past, I've had a lot of success with SparkFun's 4-bit bi-directional logic-level converter (**https://bit.ly/2WHnvRW**). Costing only US$2.95, this break-out board (BOB) can be used to convert 3.3V signals to their 5V equivalents, and vice versa (Fig.8). It can even be used with an I²C bus, which requires pull-up resistors, because the BOB has 10kΩ pull-up resisters on both sides of each channel.

Having said this, I only need to convert the signal from a single 3.3V digital output on the Seeeduino XIAO. Furthermore, I only require a unidirectional level conversion. For both these reasons, SparkFun's level-converter BOB would be overkill.

Fortunately, I ran across an awesome hack on Hackaday.com (**https://bit.ly/35LjlfL**) that provides a simple solution requiring only a single diode (a general-purpose IN4001 is perfect for this task) and a 'sacrificial' NeoPixel (Fig.9).

The way this works is that the NeoPixel's data sheet states a logic 1 value is considered to be 0.7 × Vcc. So, if we are powering the NeoPixel with 5V, a logic 1 will be 0.7 × 5 = 3.5 V. In reality, the 3.3V signal from the Seeeduino XIAO might work, but then again it might not.

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The solution is to power the sacrificial NeoPixel via the IN4001 diode. Since this diode has a forward voltage drop of 0.7 V, this means the first NeoPixel is being powered by a Vcc of 5 – 0.7 = 4.3V. In turn this means that the first NeoPixel will see a signal of 0.7 × 4.3 = 3.01 V as being a logic 1, so the 3.3 V output from the microcontroller more than fits the bill.

Meanwhile, the 4.3V Data-Out signal from the first NeoPixel is more than sufficient to drive the Data-In signal to the second NeoPixel in the chain. What this means is that we are using the first NeoPixel in the role of a voltage-level converter. In many systems, we could still use this sacrificial NeoPixel to indicate something, because it will just be a little dimmer than the other NeoPixels. In the case of my 12 × 12 ping pong ball array, however, I'll just include an extra NeoPixel before the first ping pong ball and always drive it to be black (off).

Next time

By the time I reach my next column, I'll have my 12 × 12 array up and running, so we'll be able to consider some of the programs and effects we can run on it. Until that frabjous day, have a great time, and remember that – as always – I welcome any and all comments, questions, and suggestions.

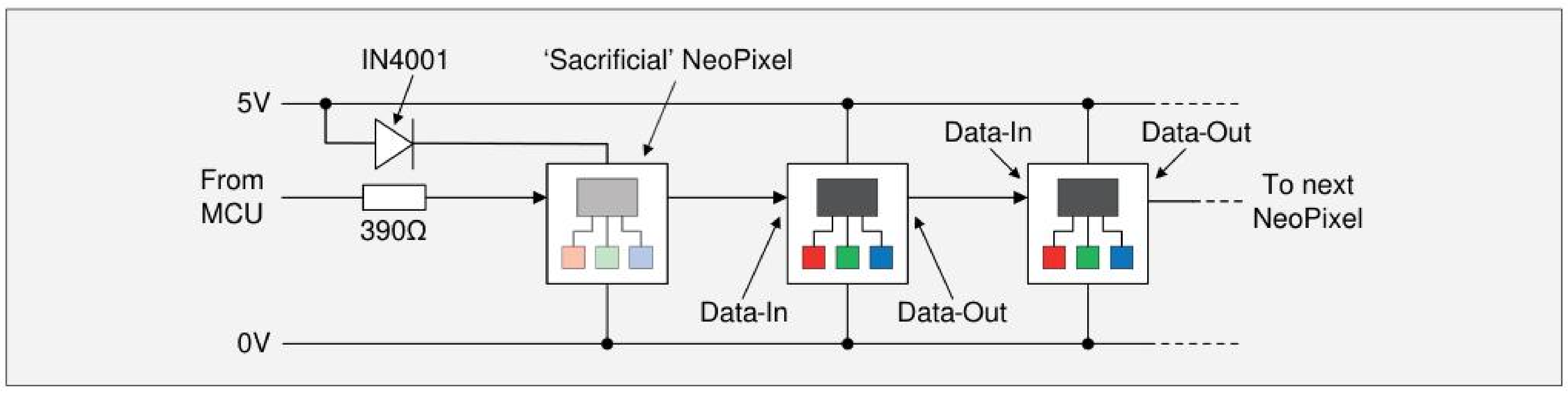


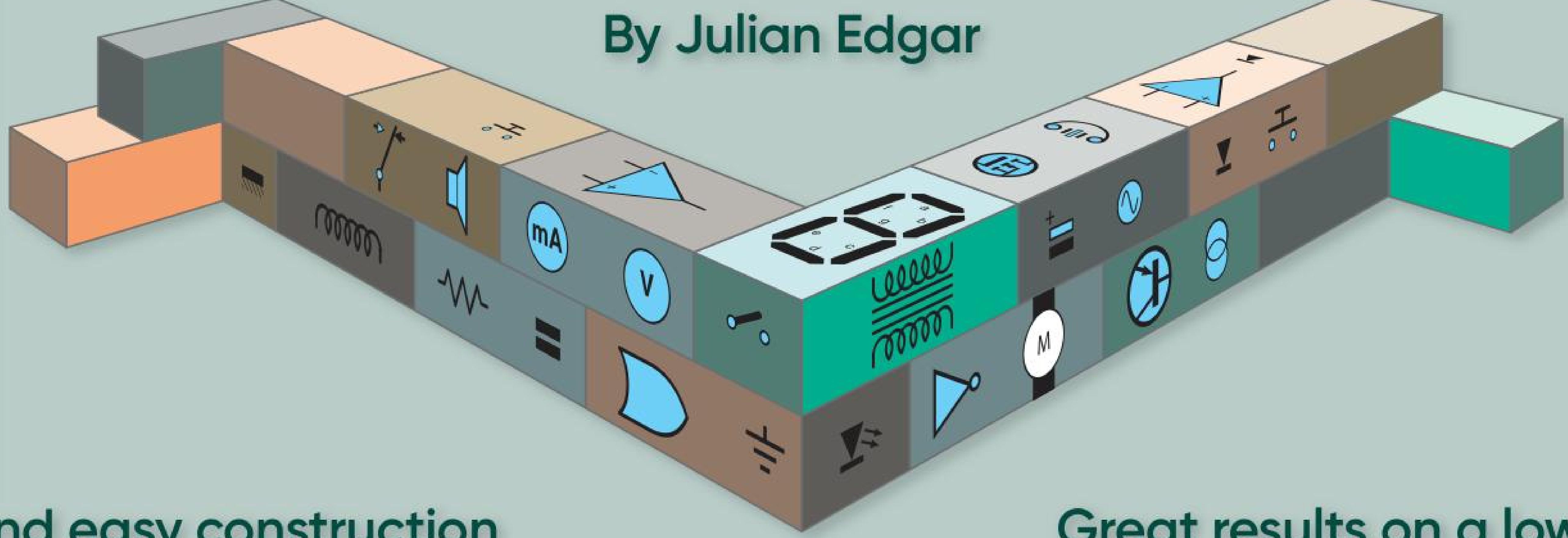
Fig.9. A cheap-and-cheerful voltage-level converter hack.

Cool bean Max Maxfield (Hawaiian shirt, on the right) is emperor of all he surveys at **CliveMaxfield.com** – the go-to site for the latest and greatest in technological geekdom.

Comments or questions? Email Max at: **max@CliveMaxfield.com**

Electronic Building Blocks

By Julian Edgar



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Modifying solar garden lights

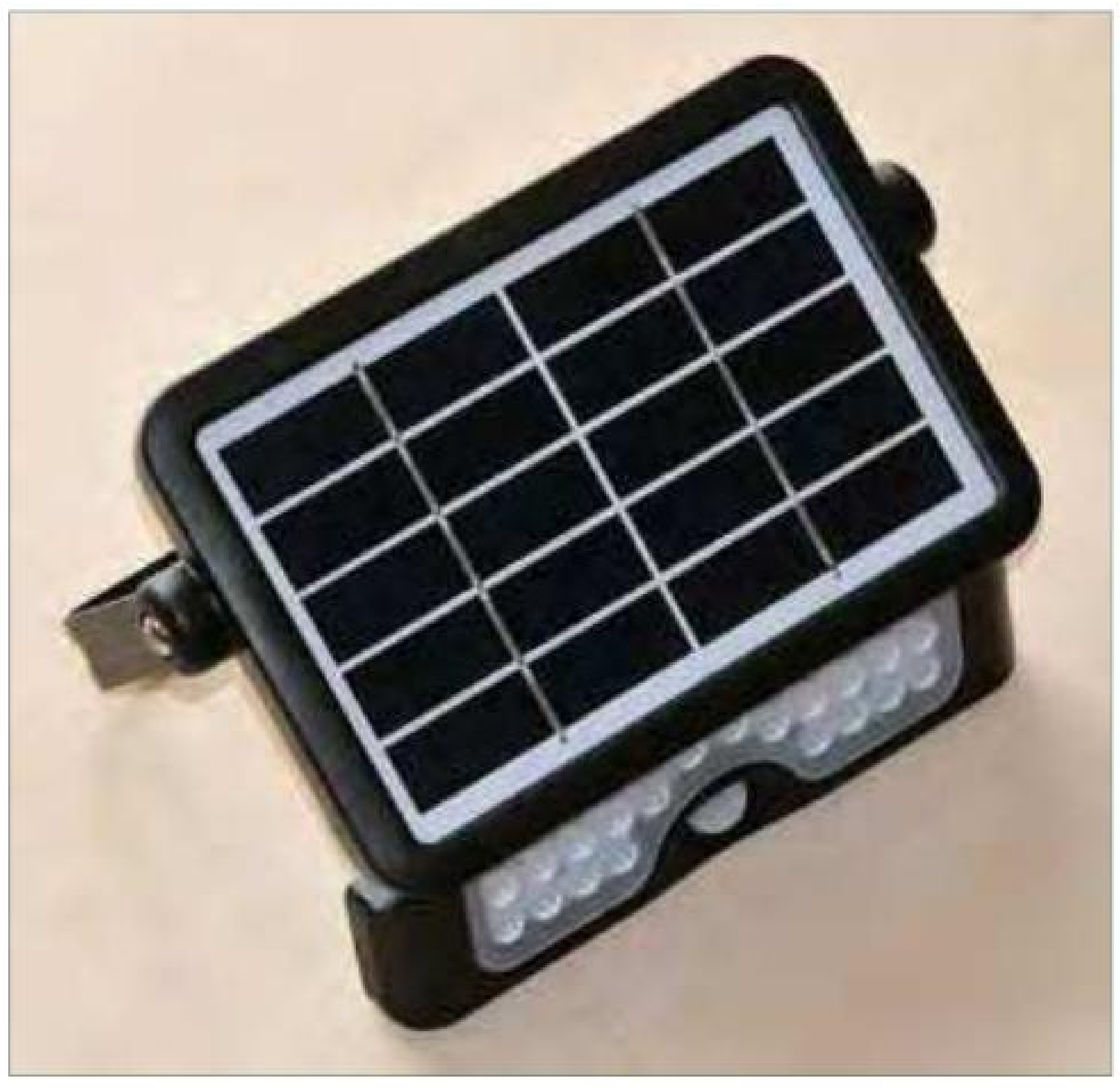

Fig.1. Good quality solar lights can be adapted to a range of uses. Try to buy those that have a decent sized solar panel and replaceable Ni-MH cells. If you wait for ‘on special’ prices, you can get lights with these attributes at very low prices – in fact, cheaper than the cost of the solar panel alone. This one cost £5.

Despite the price of solar photovoltaic panels falling dramatically over the last 10 years – in terms of cost per watt – small panels (eg, 2-5W) have remained relatively expensive. But there is a way of gaining a good quality solar panel at low cost – and as a bonus, you also get battery storage, a charge controller and an LED light! How? By buying a solar garden light. But note, not just any garden light.

Selecting

I first started looking at cheap garden lights as a source of solar power a few years ago. Since then, I have bought lots of them – but I’ve often been disappointed. Why? Well, first, many garden lights have ineffective battery storage – some even still use nickel-cadmium (Ni-Cd) batteries! (These batteries have bad memory effects, and their capacity is also much less than more modern nickel-metal-hydride (Ni-MH) batteries.) Other lights use non-replaceable, tiny batteries – flat packs about as big as your little fingernail.

Second, the cheapest solar lights often have a very low operating voltage – that is, the solar panel develops an output of only 1 or 2V. To run a white LED, they use an oscillating circuit that develops an AC output voltage, with the LED lighting-up only on the positive-going part of the waveform. To make use of the power for other purposes, you’re starting off with a very low voltage, which in turn makes everything that follows more difficult.

Finally, many solar lights hide their low power with huge reflectors. When you examine the actual source of illumination, it’s often only milliwatts.

To avoid these issues, look for a powerful light with a large solar panel that uses a replaceable Ni-MH battery – preferably comprising one or two 18650 cells.

Lights of this sort often come up as specials. (I think perhaps it’s because they’re normally much more expensive than run-of-the-mill solar lights, so people don’t buy them and hence stores discount them.)

In front of me on my desk is a good example. It uses a 2.3W solar panel, a Ni-MH battery pack comprising two 18650 cells wired in parallel, full electronic control, and a light comprising 30 surface-mount LEDs providing 550 lumens at full brightness. Furthermore, it has an inbuilt motion sensor. It’s also well made, with stainless steel hardware and good internal waterproofing… and it cost me (on special) just £5! After I’d taken one home and pulled it apart for inspection, I went back to the shop and bought a whole lot more.

Now, by the time you read this, the chance of your finding that specific light, at that price, is slim. But lights like these do pop up – and so this article is more about what you can do with such lights as and when you find them.

Adding a 5V USB output

With 5V USB power being used to do everything from charging phones and Bluetooth speakers, to running microcontroller boards and electronic instrumentation, adding a 5V USB output to the solar light immediately makes it far more useful.

In most cases, the operating voltage of the solar light is less than 5V, so you will need a boost converter. Such converters are readily available on eBay,

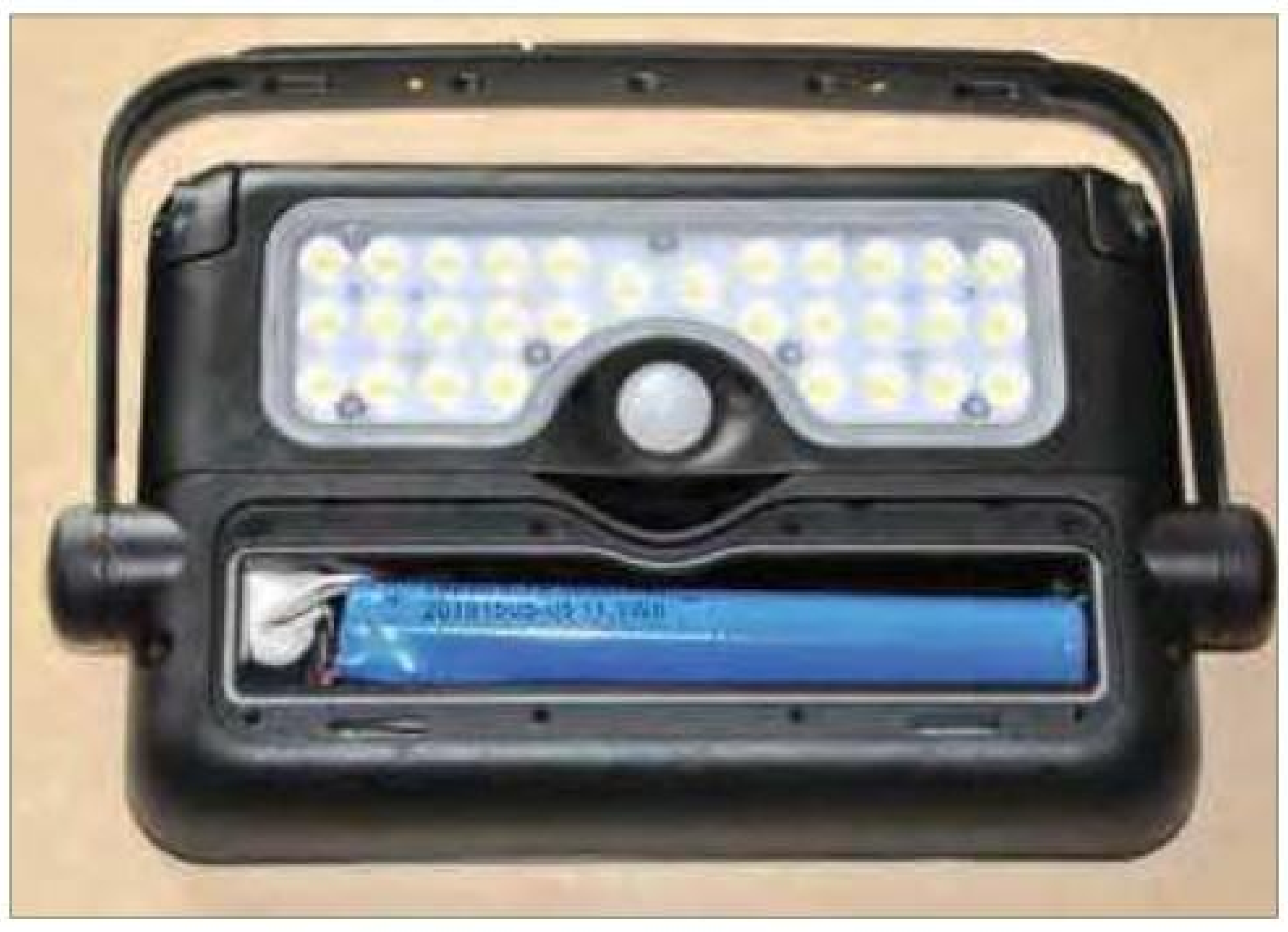

Fig.2. This light uses two 18650 Ni-MH cells. Despite appearances, they are wired in parallel, so the system operates at a nominal 3.7V. Note the seal around the battery compartment lid.

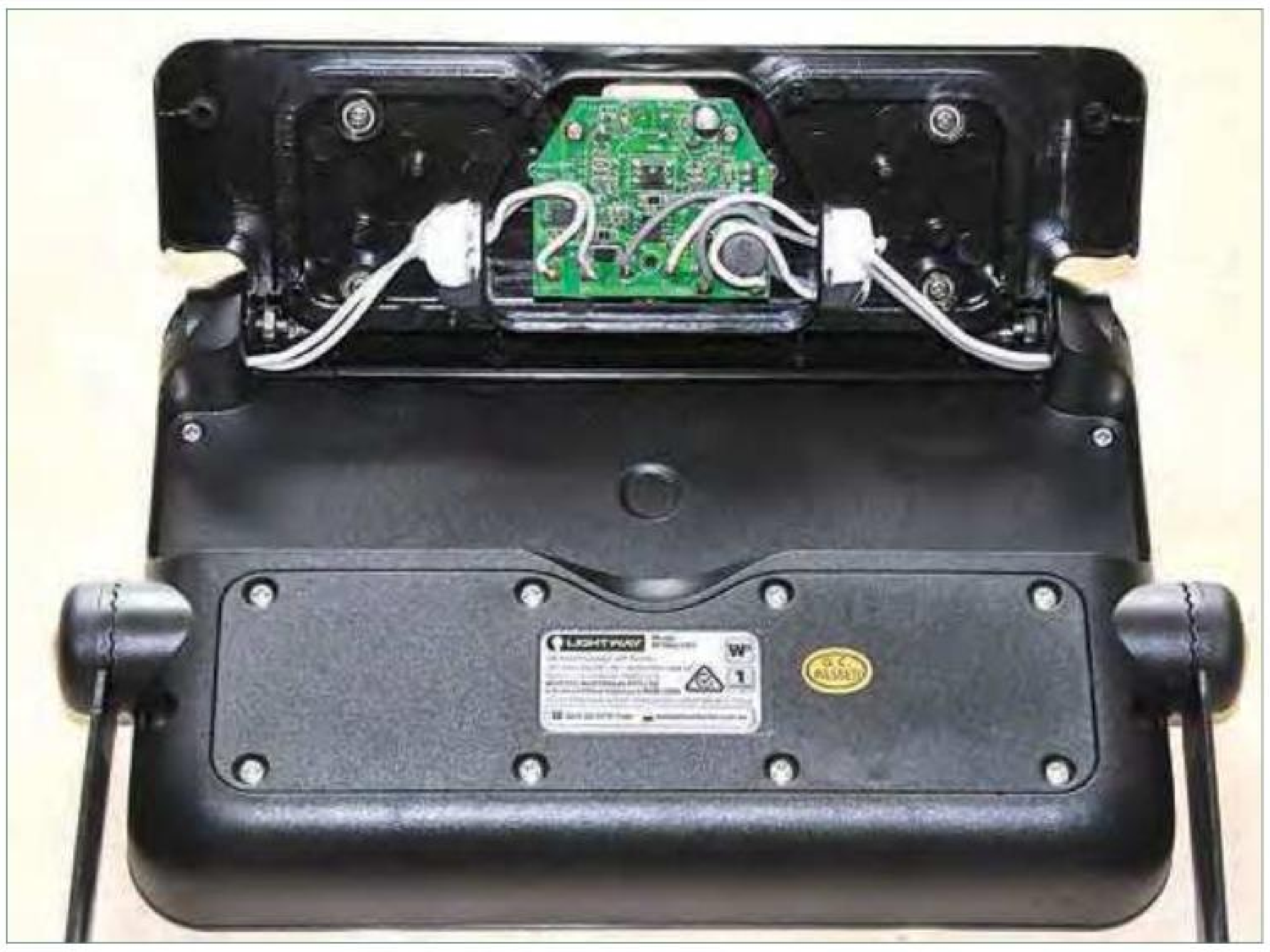

Fig.3. The electronics are mounted under the LED light panel. The PCB is well-labelled, making connecting to the panel, the LED light or the battery quite easy. When the lid to this compartment is in place, the electronics are fully sealed.

with some even incorporating the USB socket. Search under 'DC-DC 0.9-6V to 3.3-9V Solar Boost USB Adjustable Step-up Power Supply Module' or similar, and expect to pay only a few pounds. I've found that those with an adjustment pot are preferable over those with a pre-set output, because you can then set the output voltage under load. You also want the module to be as small as possible – and that's OK, because they are usually tiny.

With the solar light I purchased, there was room inside to locate the small 5V power supply board, and filing a slot in the case allowed external access to the USB socket. Of course, with the USB socket installed, the solar light is no longer waterproof. If you want the assembly to remain waterproof, then mount the board entirely inside the housing and run a charging cable out through a grommet further sealed with silicone. Depending on the use you are putting it to, you may also want to add an on/off switch for the USB supply.

Remote-mounting the LED light

Solar garden lights invariably have the panel, light, battery and electronics in one assembly. That lowers manufacturing costs and also means that you just need to 'plant' the light in the garden, aim the panel the right way and then leave it – no further work required. But such lights are far more versatile if the light can be mounted remotely. (Solar-powered lights like this are available but they tend to be much more expensive than garden lights.) So how easy is it to remote mount the LEDs? In many cases, very easy!

To remote mount the LED light, you will need to extend its connections to the rest of the assembly. Depending on the construction of the light that might require the use of just two wires – power and ground for the LEDs. But in other cases, additional connections may be needed. In the lights on which I was working, the solar panel assembly also contains the battery, so in this case, four wires were needed – two for the solar panel and two for the battery. If the light has movement sensing, ensure that the movement sensor stays with the LED light (usually the case, without any wiring changes).

When making these wiring changes, don't forget to remove the battery first. There's often no protection against a battery short-circuit – which is quite easy to achieve when extending the connections! If you are going to be making a long extension, go up in cable gauge over the original wiring to lessen the voltage drop.

Note that with the LED light remote-mounted, it will still function as it did previously. For example, the light will not illuminate until the solar panel is in the dark. So if the light is mounted inside a dark cellar, it will not operate until night has fallen outside.

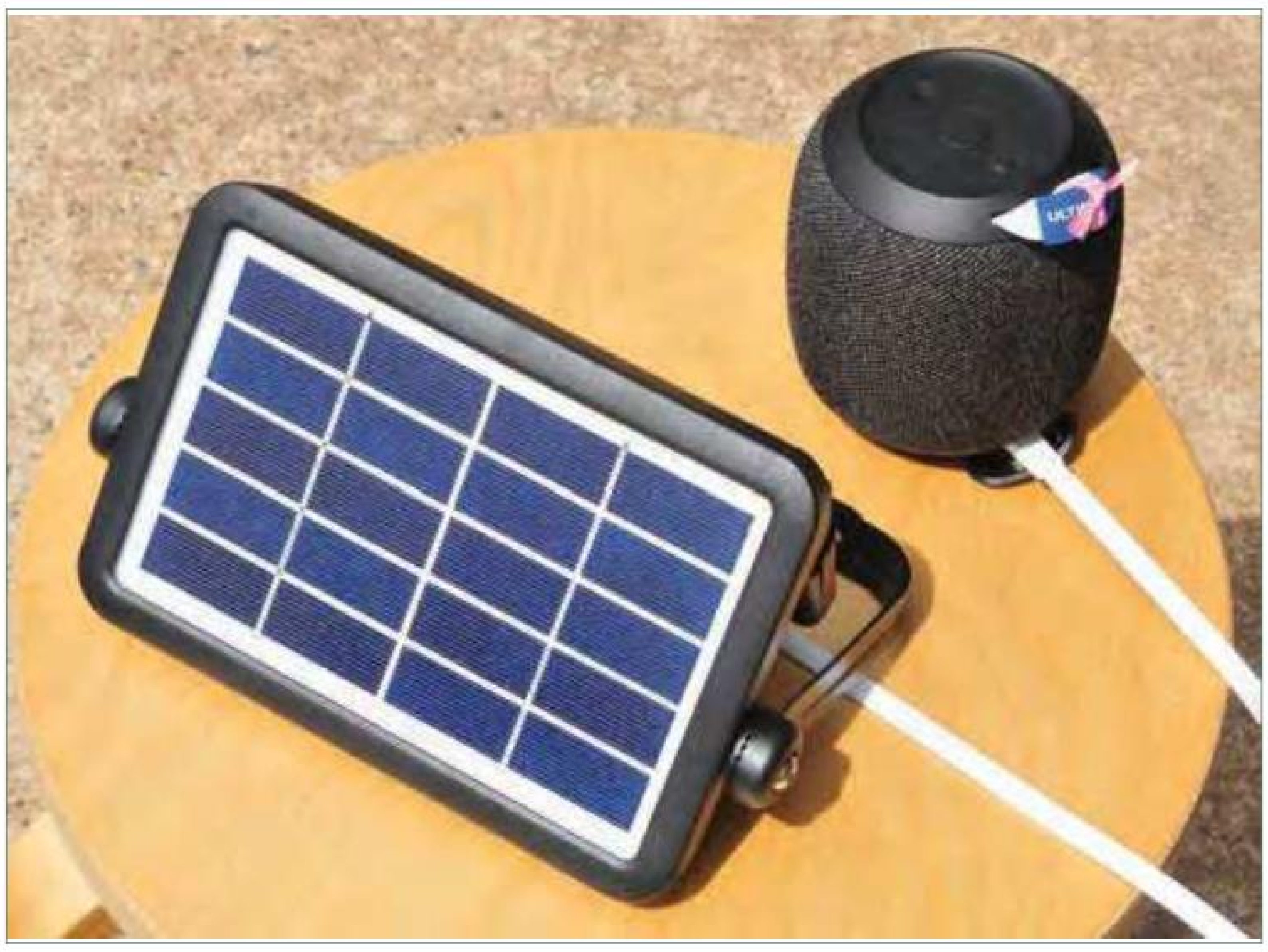

Fig.5. The solar light, fitted with a USB boost power module, charging a Bluetooth speaker.

Other uses

Good quality solar lights like the one shown here can also be used in a range of other uses; for example:

- Powering a remote transmitter – eg, for a weather station
- Add a voltage switch and buzzer – acts as a motion-sensing burglar alarm
- Emergency household or car light.

So, keep an eye out for these lights when they are being sold on discount.

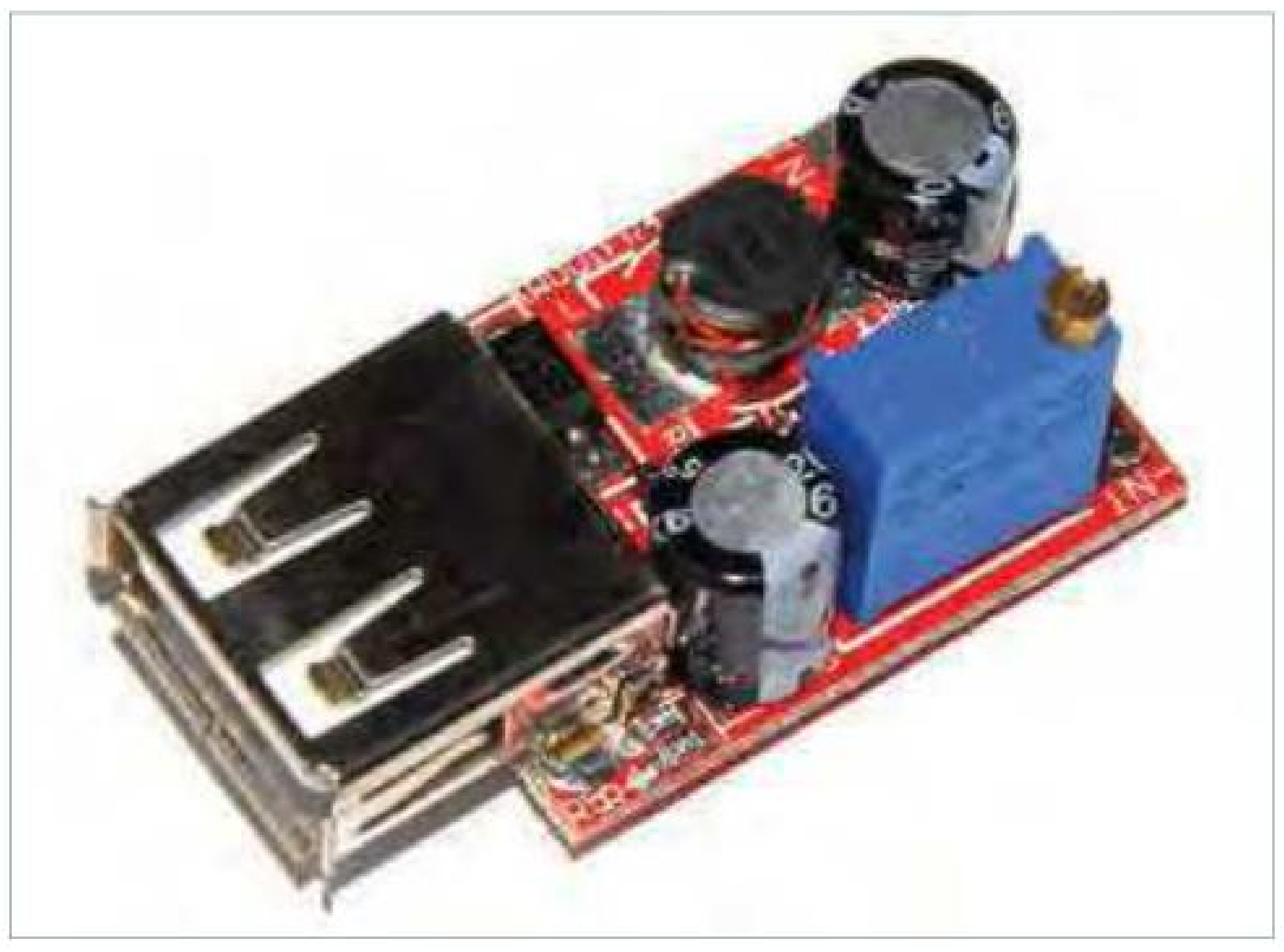

Fig.4. This boost USB converter can be easily added to make the solar light into a powerful, cheap and effective solar-charged power bank. It is also small enough to fit within the body of most lights.

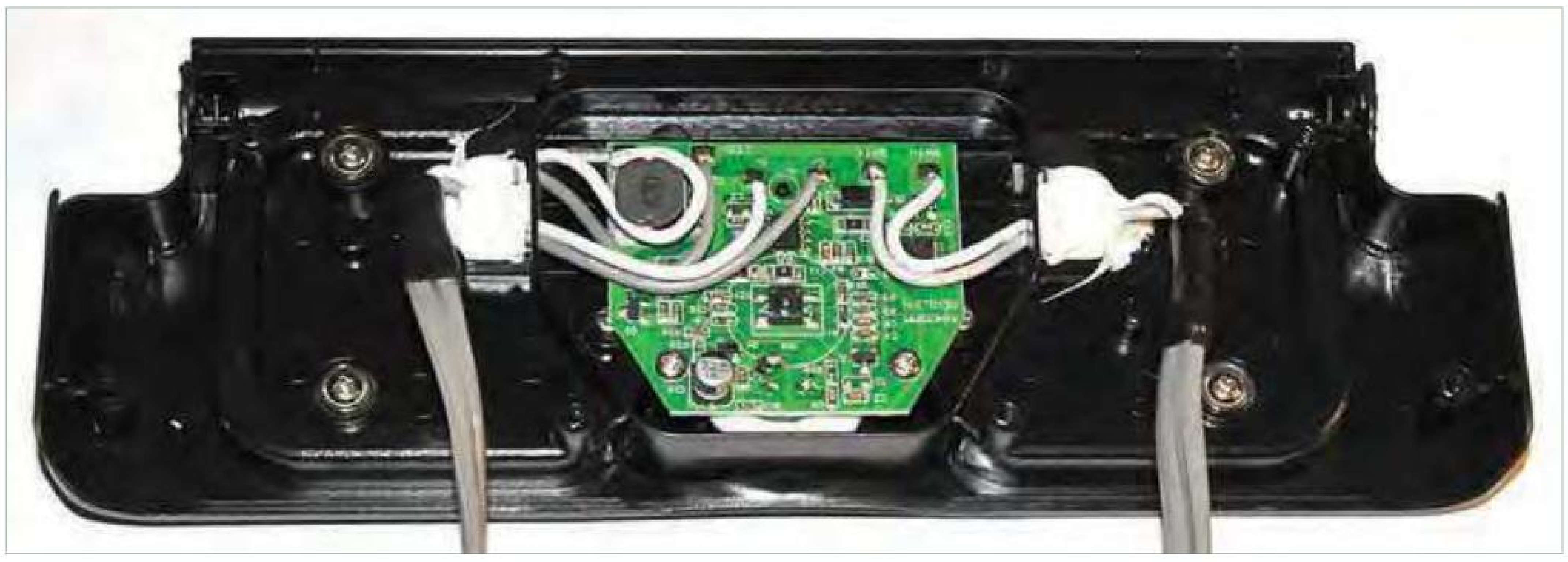

Fig.6. In some applications (for example, lighting the interior of a shed or outhouse) separating the solar panel from the light gives more versatility. In this light, where the battery is mounted on the back of the panel, connections for both the light and the battery needed to be extended. This is the rear view of the LED panel before the panel was replaced – the two new cables exit the case at the bottom of the photo.

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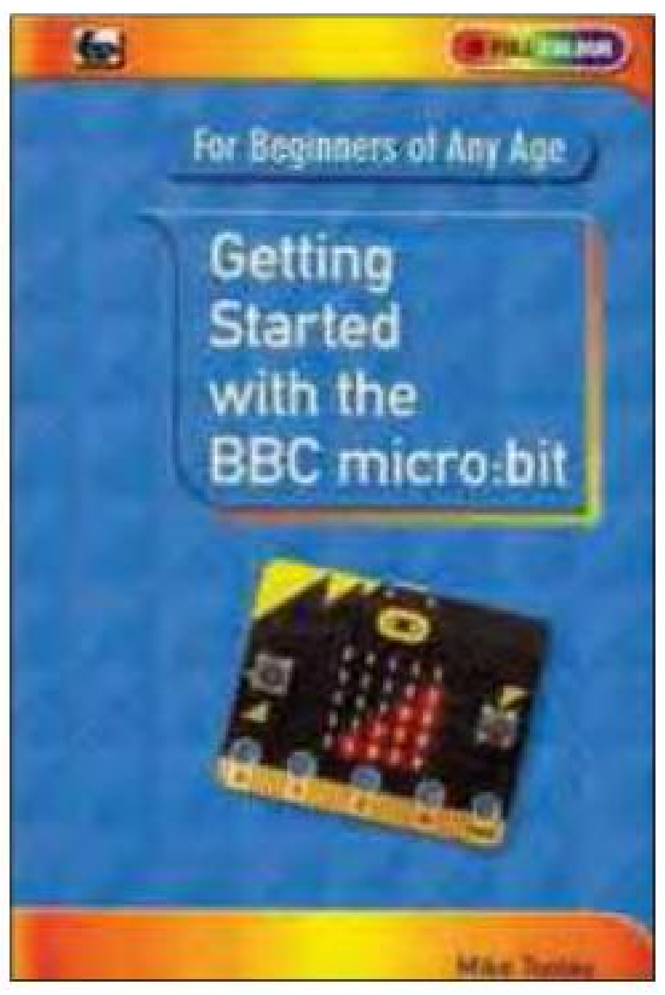

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Mike Tooley

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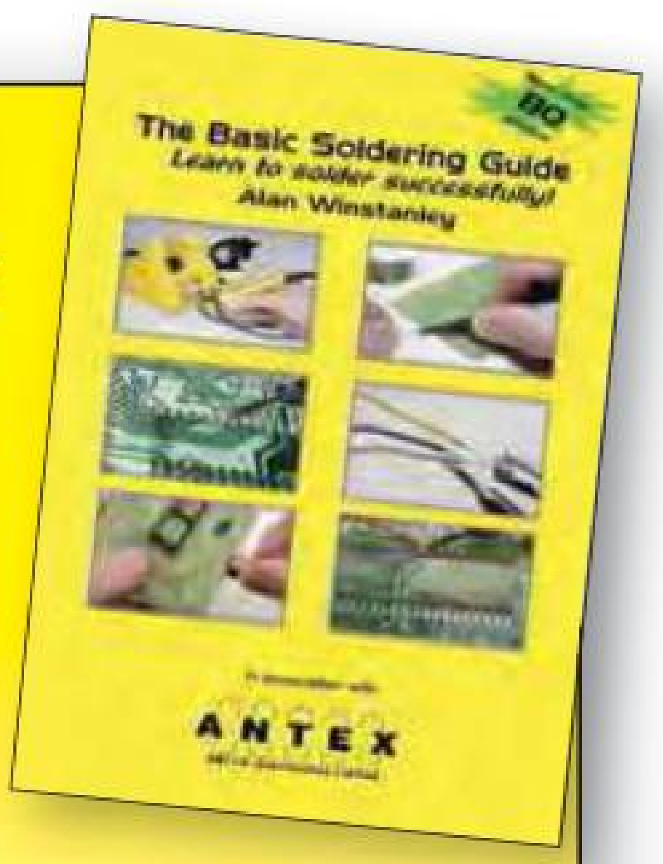

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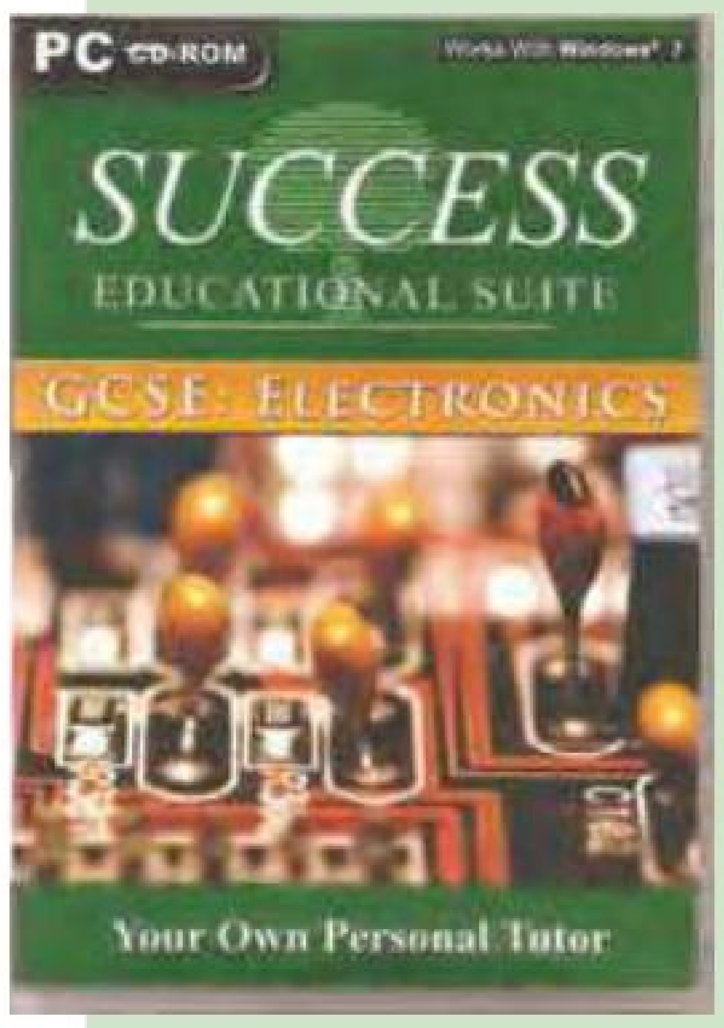

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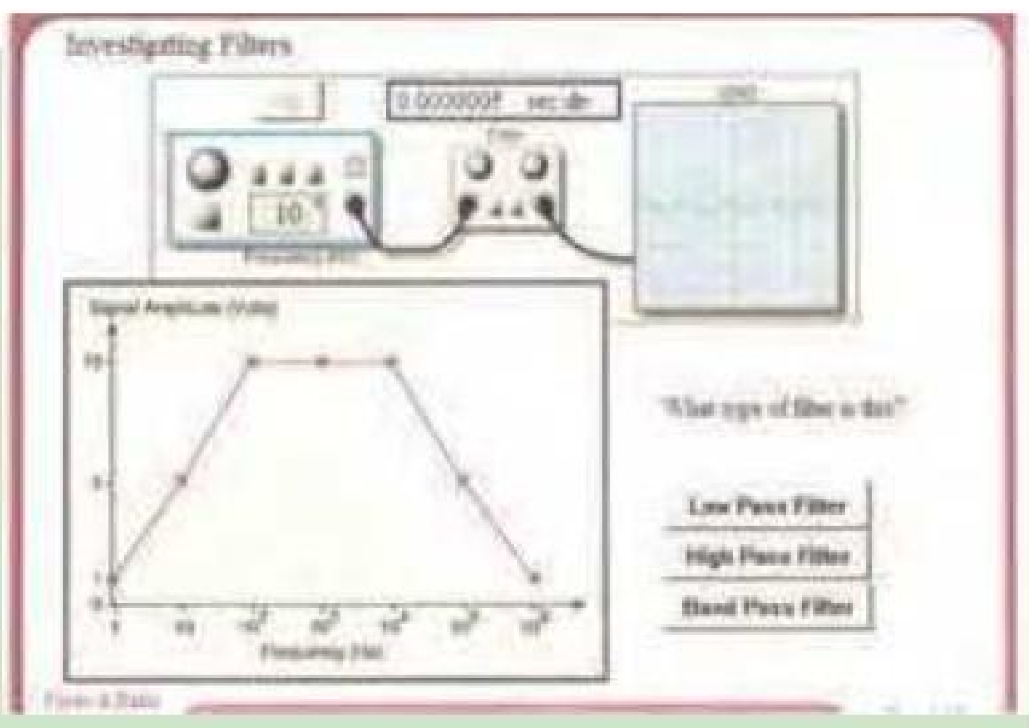

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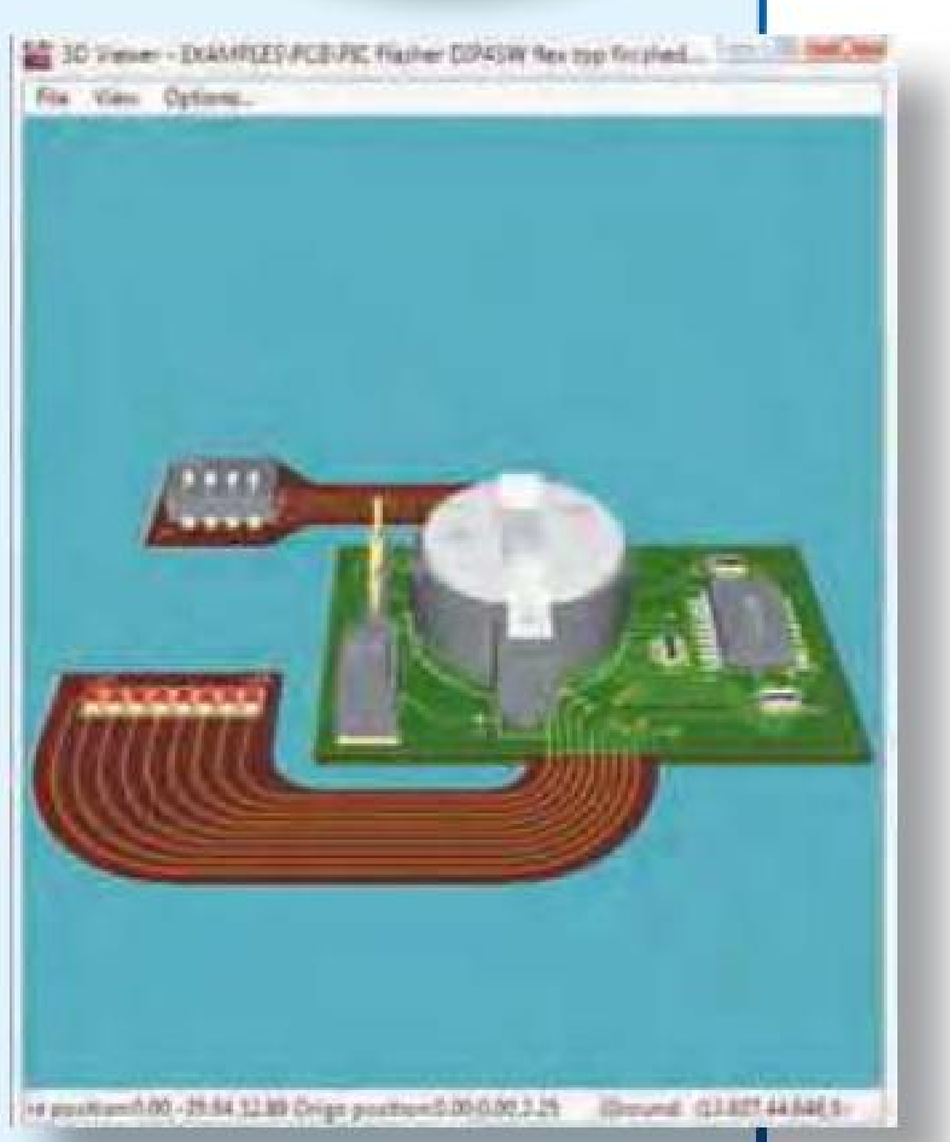

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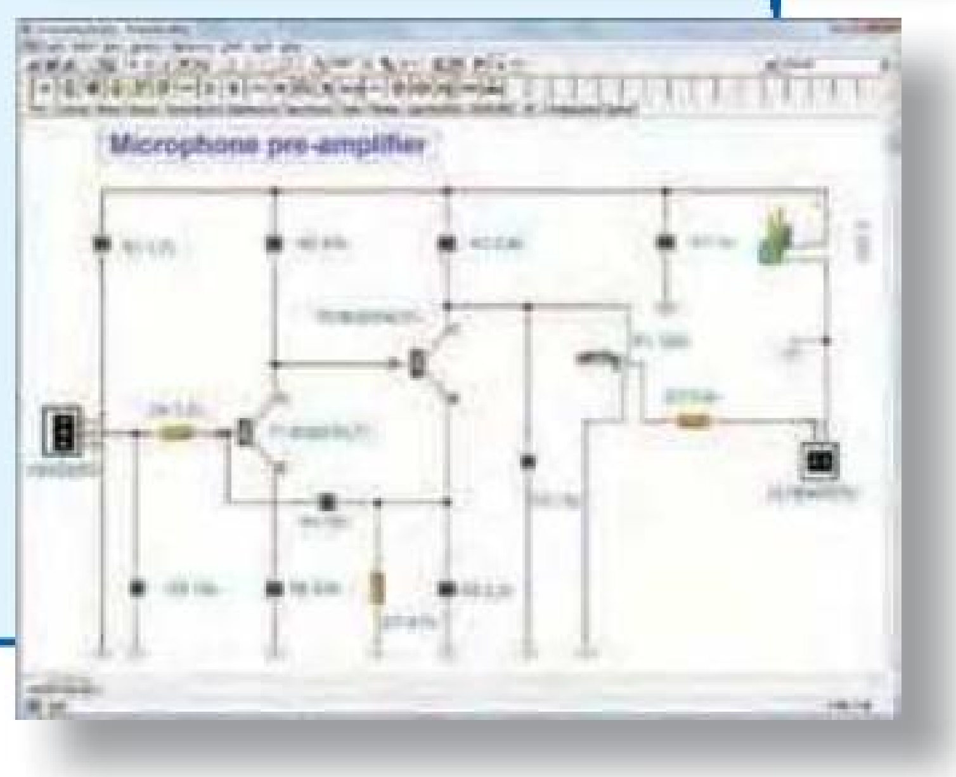

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The series is aimed at those using PIC microcontrollers for the first time. Each part of the series includes breadboard layouts to aid understanding and a simple programmer project is provided.

Also included are 29 *PIC N' Mix* articles, also republished from *EPE*. These provide a host of practical programming and interfacing information, mainly for those that have already got to grips with using PIC microcontrollers. An extra four part beginners guide to using the C programing language for PIC microcontrollers is also included.

The CD-ROM also contains all of the software for the *Teach-In 2* series and *PIC N' Mix* articles, plus a range of items from Microchip – the manufacturers of the PIC microcontrollers. The material has been compiled by Wimborne Publishing Ltd. with the assistance of Microchip Technology Inc.

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The second section – *Practically Speaking* – covers the practical aspects of electronics construction. Again, a whole range of subjects, from soldering to avoiding problems with static electricity and indentifying components, are covered. Finally, our collection of *Ingenuity Unlimited* circuits provides over 40 circuit designs submitted by the readers of *EPE*.

The CD-ROM also contains the complete *Electronics Teach-In 1* book, which provides a broad-based introduction to electronics in PDF form, plus interactive quizzes to test your knowledge, TINA circuit simulation software (a limited version – plus a specially written TINA Tutorial).

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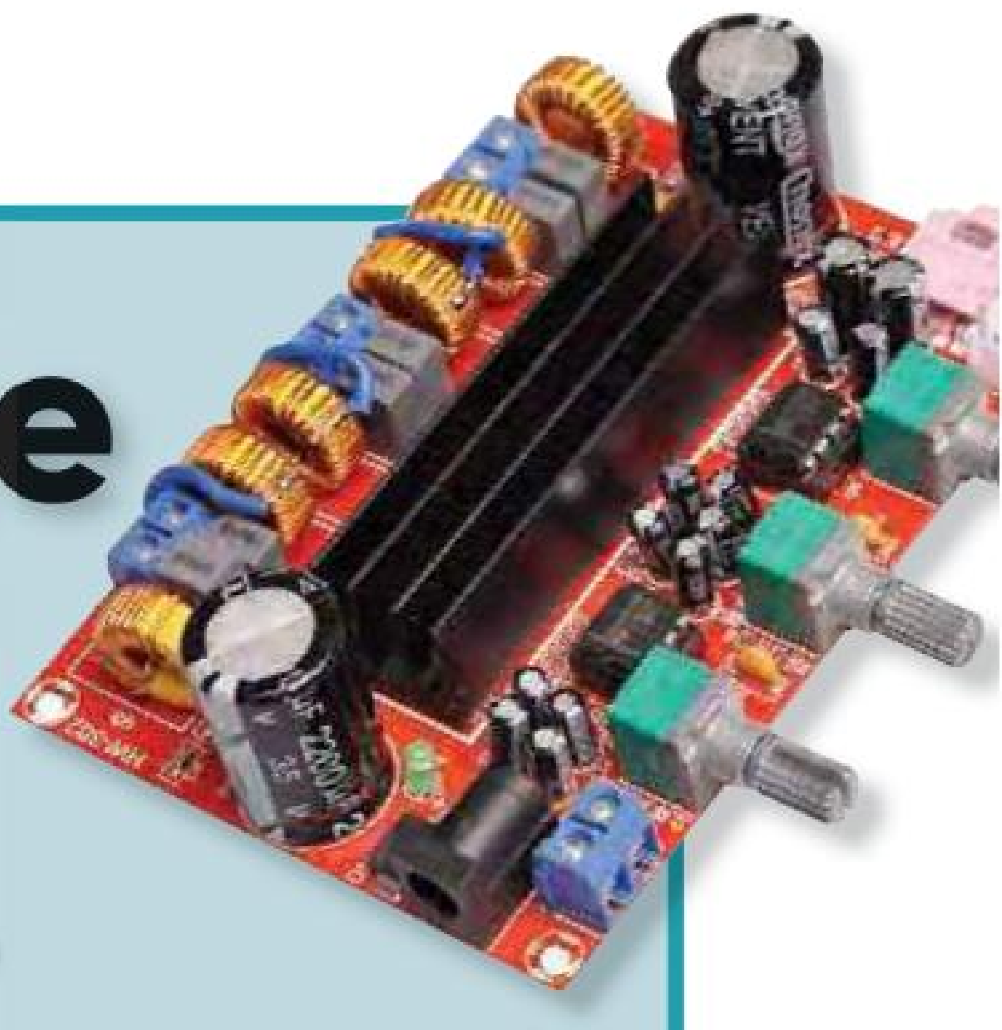
Next Month – in the August issue



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This *BackPack* is the most convenient and powerful yet. It supports both 2.8-inch and 3.5-inch touchscreen displays, plus five new optional features, including extra memory, temperature, humidity and pressure sensors, a real-time clock, an infrared receiver and more!

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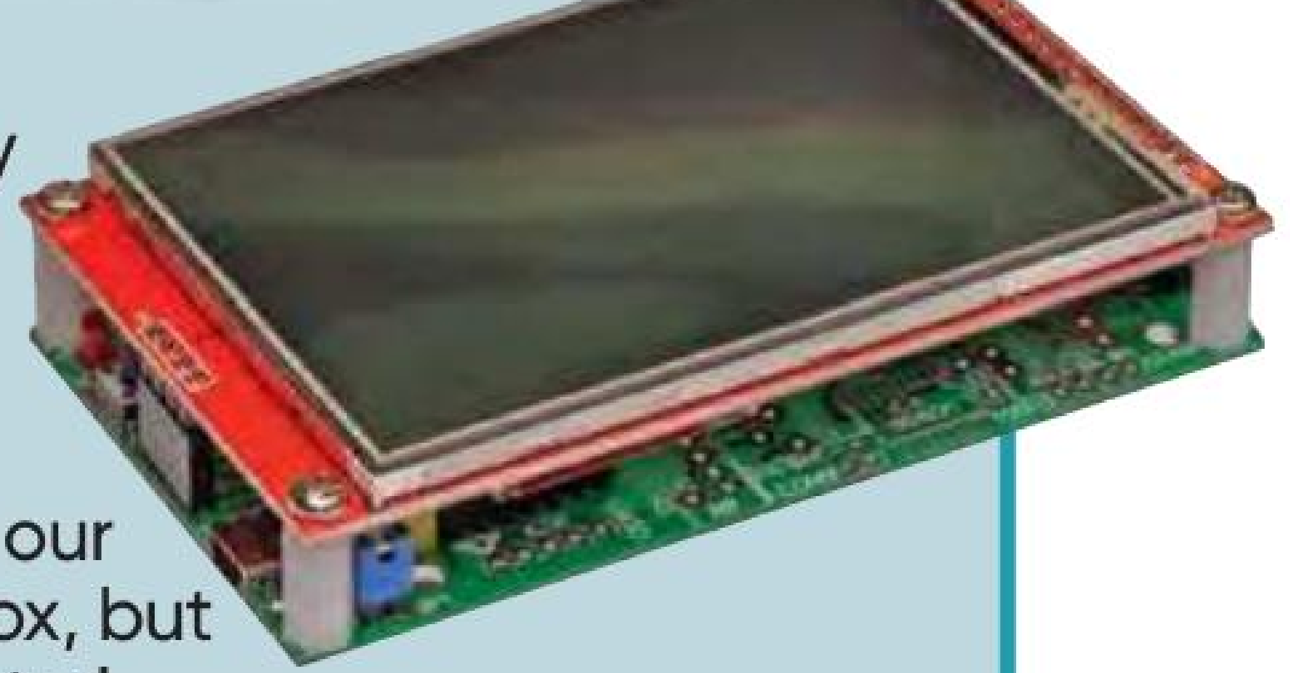
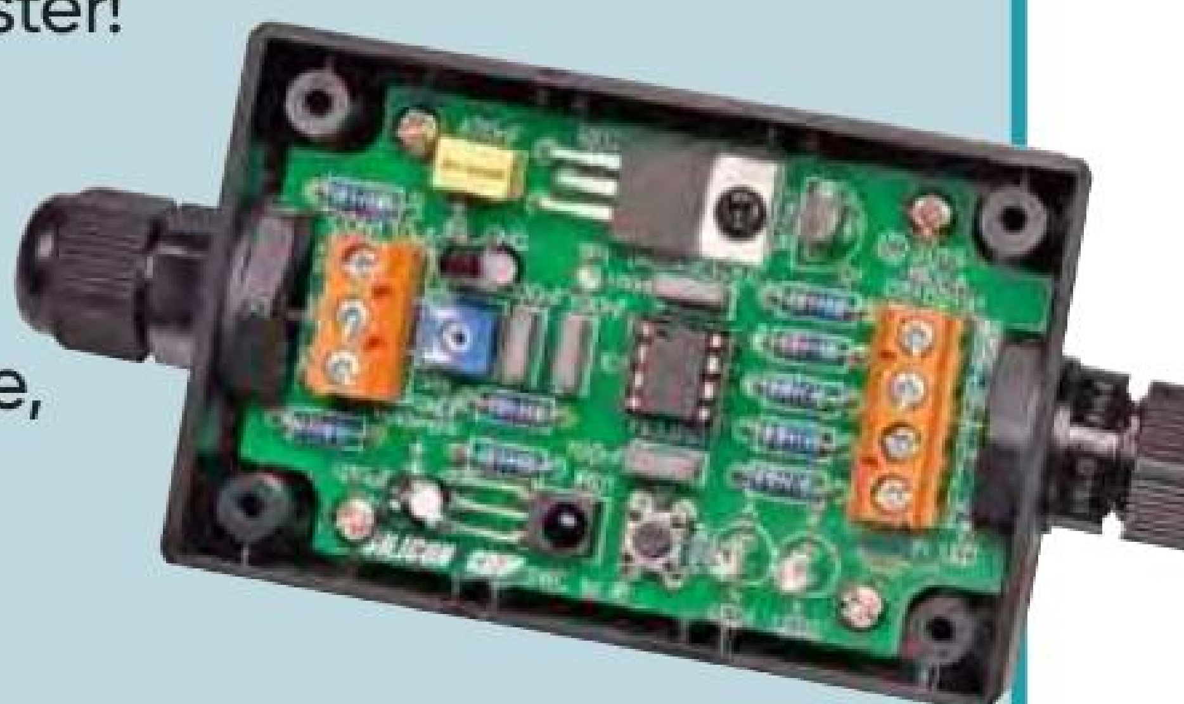


Junk Mail Repeller!

Is your letterbox full of junk, even though you have a 'NO JUNK MAIL' sign? If so, you need our *Junk Mail Repeller*. It might not completely prevent junk mail from being shoved in your box, but it should help. And you'll have some fun watching the reactions of the would-be junkmeister!



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